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A Membrane-Based Subsystem for Water-Vapor Recovery From Plant-Growth Chambers

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A Membrane-Based Subsystem for Water-Vapor Recovery From Plant-Growth Chambers

R. J. Ray

Bend Research, Inc.
64550 Research Road
Bend, Oregon 97701-8599

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Ames Research Center
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NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

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SUMMARY

Key to the successful development of practical Controlled Ecological Life Support System (CELSS) technology is a subsystem to control the temperature and humidity in plant-growth chambers (PGCs). The Phase I objective was to develop the basic technology needed for a simple, reliable, membrane-based subsystem that allows for the recovery and reuse of transpired water vapor through control of temperature and humidity levels in PGCs.

We accomplished this objective by successfully testing the components of a subsystem based on two basic technologies: 1) a membrane-contactor module operated as an evaporative cooler, and 2) a membrane-contactor module operated as a water-recovery heat exchanger. The evaporative cooler increases the humidity in the PGC and, in so doing, helps cool the air in the PGC. The water-recovery heat exchanger removes water vapor from the PGC and cools the air circulated through the chamber.

The objectives of the Phase II program are 1) to further develop the membrane-based subsystem by developing membrane modules designed specifically for this application and by designing the configuration of the subsystem itself; and 2) to design, test, and deliver a breadboard subsystem to NASA.

I. INTRODUCTION AND SUMMARY

This is the Phase I final report from Bend Research, Inc., (BRI) to NASA on work performed under Phase I of Small Business Innovation Research Contract No. NAS 2-13345, entitled "A Membrane-Based Subsystem for Water-Vapor Recovery from Plant-Growth Chambers." The Phase I period of performance was January 8 to July 8, 1991.

I.A. BACKGROUND

Bioregenerative systems--usually plant-based life-support systems to regenerate oxygen, food, and water--are key to establishing man's permanent presence in space. NASA's Controlled Ecological Life Support System (CELSS) program is focused on generating the baseline data and support technology necessary for plants to be an integral part of the life-support systems needed for extended missions. An operating CELSS will serve several important purposes, including 1) oxygen and food production; 2) carbon dioxide removal; and 3) water recovery, purification, and reuse.

Key to the successful development of practical CELSS technology is a subsystem to recover and reuse the water vapor transpired from the leaves of the closely packed plants in the closed environment of a plant-growth chamber (PGC). Also necessary is the efficient removal of the substantial amounts of heat introduced into the PGC by the growth lights required in these closed chambers (Blackwell et al., 1991; MacElroy and Brendt, 1984; Tri et al., 1991).

I.B. SUMMARY OF PHASE I RESULTS

The objective of this Phase I program was to develop the basic technology needed for a simple, reliable membrane-based subsystem that allows the recovery, purification, and reuse of the transpired water vapor--through control of the temperature and humidity levels in the PGC. We achieved this objective.

I.B.1. Preliminary Phase I Results

In the Phase I proposal and through the first half of the Phase I program, we focused on the development of a temperature-control and water-recovery subsystem based on two appropriate membrane technologies. This subsystem employed 1) membrane-based dehumidification modules to remove water vapor from air; and 2) "membrane contactor" technology to return water vapor to the CELSS chamber (and in so doing control the temperature and humidity levels within the PGC). The dehumidification module was studied sufficiently early in the program that we were able to design, construct, and deliver a small demonstration unit to Ames Research Center (ARC) for use on their "Salad Machine."

Figure 1 shows a schematic of this dehumidification membrane technology. The driving force for water-vapor transport across this membrane is a vacuum pump, which lowers the partial pressure of water on the permeate side of the membrane module. This vacuum "pulls" water vapor from the PGC, across the membrane, and into the permeate side of the membrane. The water vapor is then compressed by a vacuum pump and condensed in a phase separator. After evaluating the demonstration unit, Ames personnel

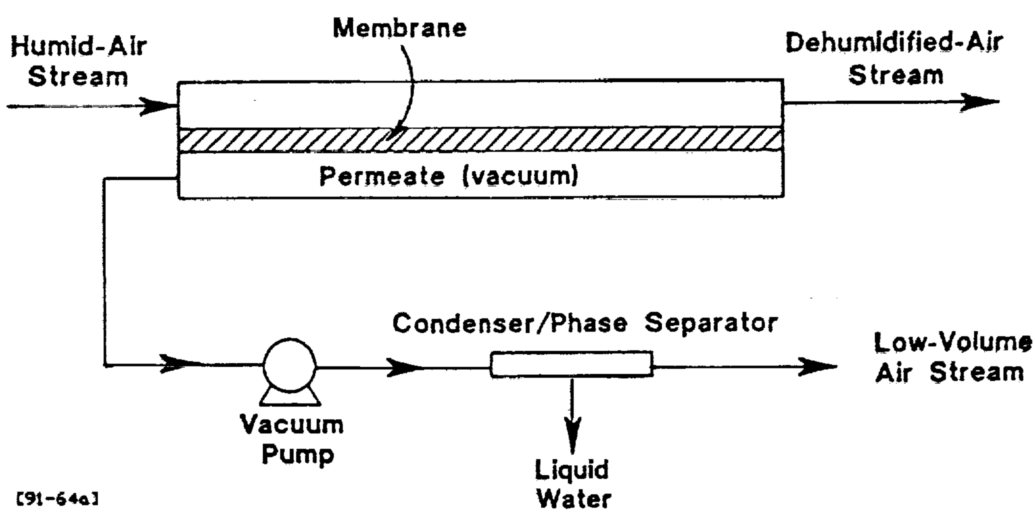

Figure 1. Dehumidification Membrane Technology Originally Proposed and Delivered to ARC in Phase I. Based on feedback from ARC personnel, this technology was replaced by the Water-Recovery Heat Exchanger (WRHE) (see Section I.B.2.)

determined that this vacuum-driven technology, while having some important advantages, was too complicated and bulky. The results of this work appear in Appendix A.

I.B.2. Final Phase I Results

Given the feedback from Ames, we abandoned the vacuum-driven technology shown in Figure 1 and described in Appendix A. We spent the last half of the Phase I program conceiving, developing, and testing a "Water Recovery Heat Exchanger" (WRHE). This hollow-fiber membrane device is shown schematically in Figure 2. As shown in the figure, the WRHE cools and removes water vapor or water droplets from the feed-air stream without the need for a mechanical driving force such as a vacuum pump. In fact, the WRHE requires only a low-power air blower and a small stream of recirculated chilled water.

This new device is ideal for the removal and recovery of water vapor, as well as for the removal of substantial amounts of heat from CELSS chambers. Study of NASA-related literature indicates that there is a general need for a device such as the WRHE for the separation of water vapor or water droplets from a

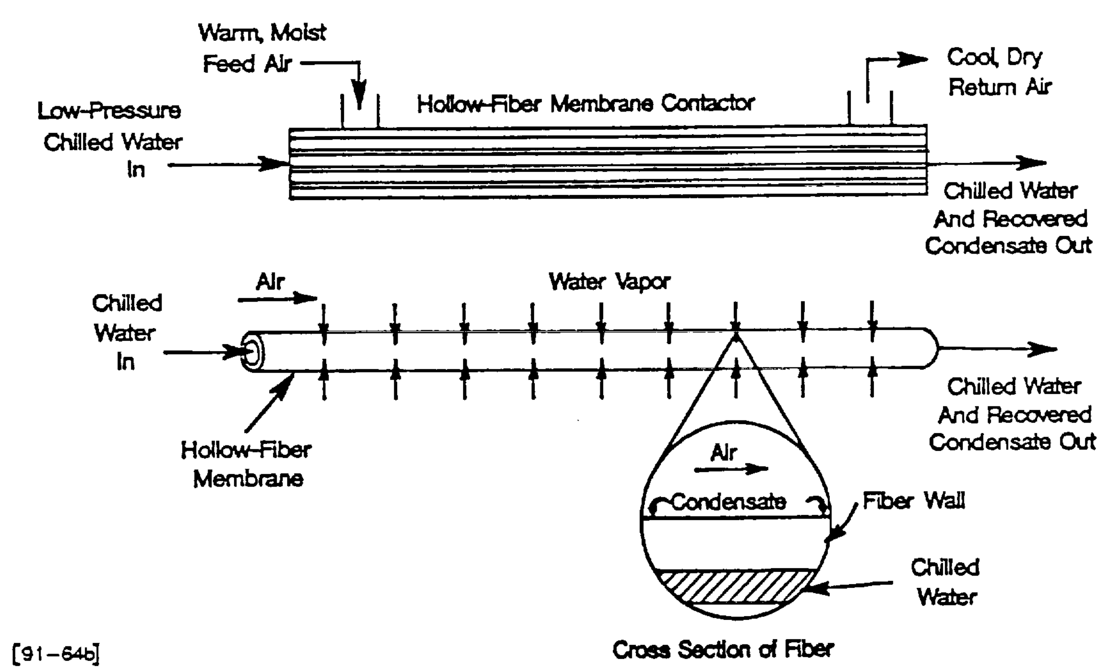

Figure 2. Schematic of WRHE

variety of air streams in microgravity environments. We are currently applying for a patent on this technology.

In the last half of the Phase I program, we also completed preliminary laboratory testing of the membrane-contactor-based "Evaporative Cooler" (EVCR) technology shown in Figure 3. In the EVCR, the water vapor is transported into the incoming air stream, while in the WRHE, it is transported out of the air stream.) This module also requires only a small air blower and a stream of water. It can substantially cool an air stream through the evaporation of a small amount of water vapor, and it will be effective in a microgravity environment.

In the modeling studies performed in Phase I, these two technologies were combined into a water-vapor and heat-recovery subsystem of the general configuration shown in Figure 4. The subsystem is designed to facilitate simple process control under the variable conditions observed in a CELSS chamber. In this design, the WRHE is sized for the removal of an amount of water vapor equivalent to the maximum expected plant-transpiration rate. The WHRE also removes a substantial fraction of the heat that must be removed to keep the chamber temperature constant.

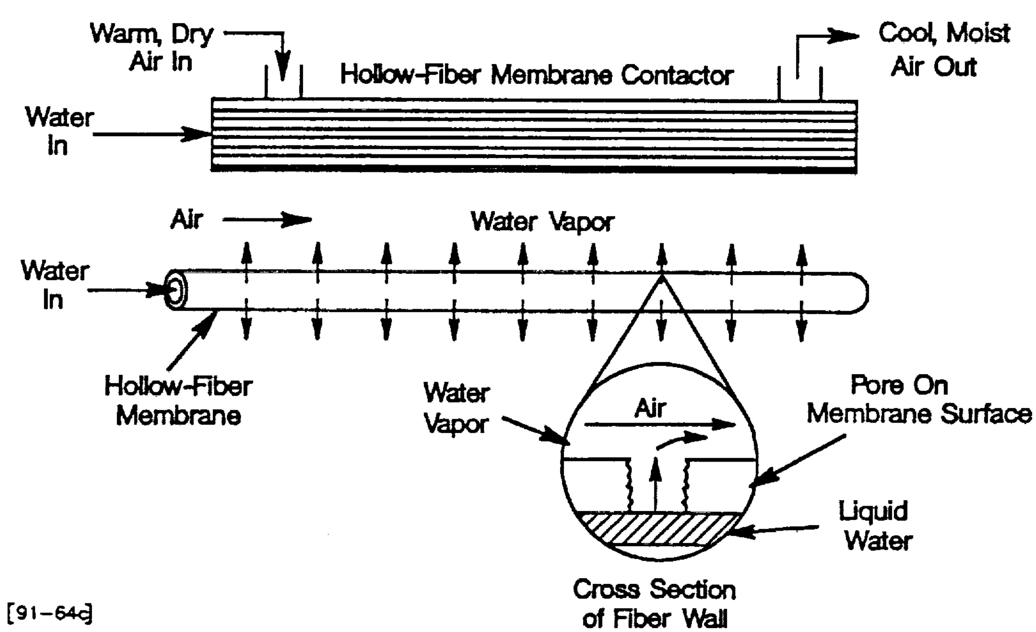

Figure 3. Schematic of EVCR

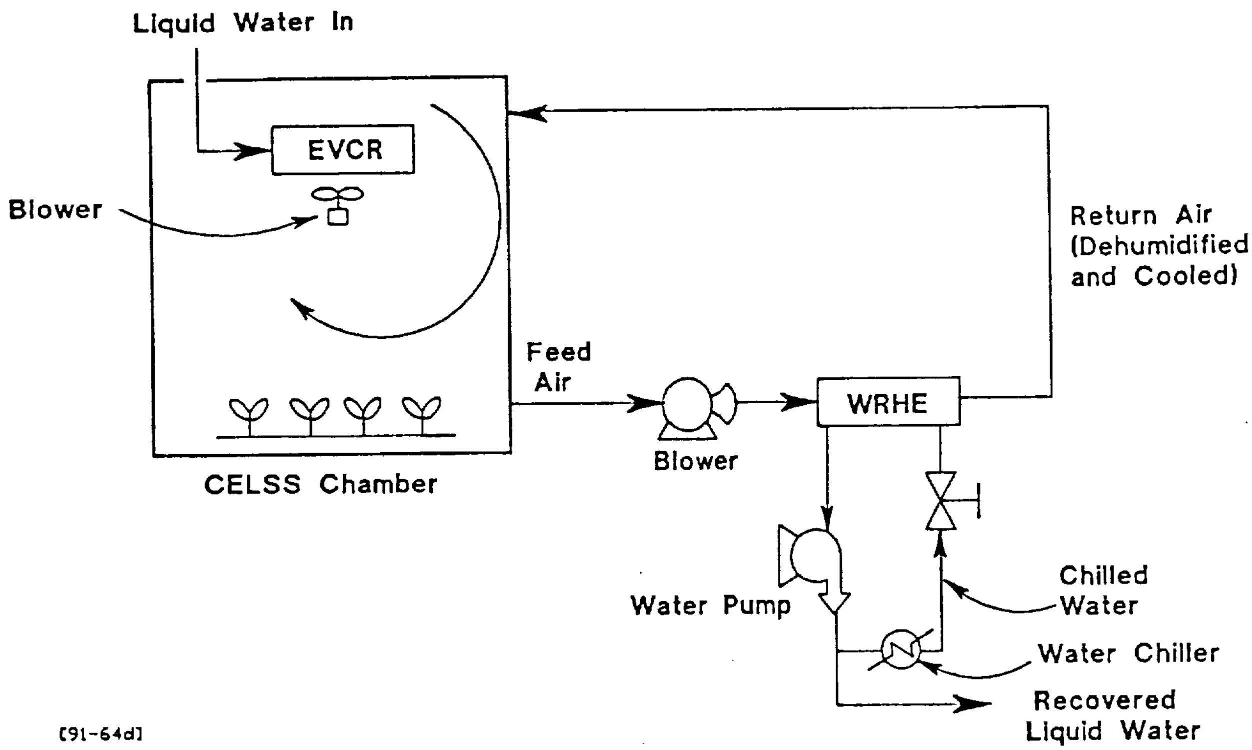

Figure 4. Simplified Schematic of Final System, Showing:
1) EVCR in CELSS Chamber for Cooling by Evaporation,
2) WRHE for Cooling and Dehumidification, and
3) Chilled-Water System for WRHE

As is shown in Figure 4, an EVCR is placed in the CELSS chamber. Process-control logic causes the EVCR to evaporate an amount of water vapor into the chamber such that, when added to the actual plant-transpiration rate at any given time (almost always less than the maximum), it equals the maximum amount ever to be observed. This keeps the load on the WHRE constant and results in the humidity of the chamber section being controlled to the desired level. The evaporation of water in the EVCR also cools the air, helping to maintain the dry-bulb temperature of the chamber at the set point.

This subsystem has several key advantages.

1. Water vapor and water droplets from air are separated by non-mechanical means (the WRHE).
2. Heat is removed concurrently from the PGC (that is, the considerable energy introduced into the CELSS chamber by the lights is removed in the form of sensible heat from the air and sensible and latent heat in the water

vapor). This heat is transferred to the cool water circulated through the WRHE as water vapor is removed, or to the water vapor molecules that are vaporized by the EVCR.

3. The subsystem configuration is simple. The subsystem uses only circulating chilled water and low-power air blowers.
4. Control of temperature and relative humidity is simple. The inherent characteristics of this subsystem result in control of temperature and relative humidity (RH) based on dry-bulb temperature measurement and the on-off or variable-speed control of the air blowers. No delicate humidity-sensing (or any other sensing) devices are required.
5. Finally, this subsystem configuration allows the maintenance of several growth zones within the PGC--each with conditions ideal for growing a specific type of plant. There is evidence that specific plants may favor slightly different RH levels and temperatures for optimal growth rates (Kliss, 1991; Wheeler, 1991). The use of EVCRs in small subchambers will allow such zones to be maintained.

We believe that the WRHE and EVCR technologies, when combined into the subsystem proposed here, will meet NASA's requirements for environmental control of CELSS chambers. These technologies and this subsystem concept were developed through a combination of innovation by BRI and input from NASA personnel regarding the needs for PGC environmental control.

II. BACKGROUND

II.A. NASA PLANT-GROWTH CHAMBERS (PGCs)

NASA has mounted a substantial research and development effort on bioregenerative systems designed to produce oxygen, food, and water for long-duration space flights and for manned bases. A key challenge in this area is the need to grow plants in space. Plants and other biological processes, when combined with physiochemical regeneration technology, have the potential to come much closer to closing the regeneration loop than do conventional methods alone (MacElroy and Brendt, 1984).

Higher plants, such as those typically grown for food, consume carbon dioxide, produce oxygen, and reclaim water via transpiration (Tri et al., 1991). The challenge is to provide a controlled environment for these plants that will optimize their growth rates for food production and, at the same time, allow them to perform their regeneration tasks efficiently.

To improve the understanding of plant responses in closed systems and to provide a basis for environmental control and associated regeneration technology, NASA has set up a broad-based program known as the CELSS program (Bubenheim et al., 1991). Under this program, NASA personnel and NASA contractors are performing fundamental studies of plant growth under closed-environment conditions. These studies continue to provide much-needed data for the design of environmental control and harvesting techniques.

Under the CELSS program at ARC, NASA personnel are engaged in a variety of studies of plant growth in micro- or low-gravity situations. One ARC program is the so-called "salad machine." This small PGC is intended as an "appliance" for producing a variety of vegetables. As currently envisioned, the salad machine will have some environmental-control technology associated with it, but will not be completely closed from the cabin environment. The salad machine provided a convenient test bed for our Phase I studies.

A goal of another CELSS program at ARC is to flight-test a small CELSS chamber in the near future. One of the aims of the work proposed here is to develop technology to support this CELSS flight test.

Plant-growth chambers have been constructed at other NASA centers under the CELSS program. For example, at Johnson Space Center, NASA personnel are constructing the Regenerative Life Support Systems (RLSS) Test Bed to study higher plants in a closed, controlled environment in conjunction with physicochemically based life-support systems (Tri et al., 1991). At Kennedy Space Center, a biomass-production chamber has been constructed and is being operated to study cultural practices, crop physiology, crop pathology, microbiology, nutrient chemistry, and nutrient delivery systems (Prince et al., 1987).

II.B. CONVENTIONAL WATER-VAPOR AND HEAT-REMOVAL TECHNOLOGY

II.B.1. Subsystems Using Condensing Heat-Exchanger Technology

Efficient use of the limited plant-growing space in a CELSS chamber necessitates very high plant-growth densities. Furthermore, the anticipated optimal growth conditions present in these chambers result in large amounts of water vapor being transpired in these closed chambers. The recovery of this water is, of course, important for the life-support function of the chamber. Equally important is the removal of this water vapor, and the heat introduced to the CELSS chamber by the growth lights and other equipment, in a way that maintains the desired environmental conditions.

"Conventional" technology developed by NASA for removal of water vapor is based on condensing heat exchangers, coupled with a device for separating the resulting air and liquid-water stream into air with a lower water content, and liquid water with a minimum of dissolved and entrained air. Such a subsystem is shown in Figure 5. Table I summarizes the state points and energy inputs to the components of this conventional subsystem.*

* This subsystem was designed by Bend Research based on our current understanding of this conventional technology.

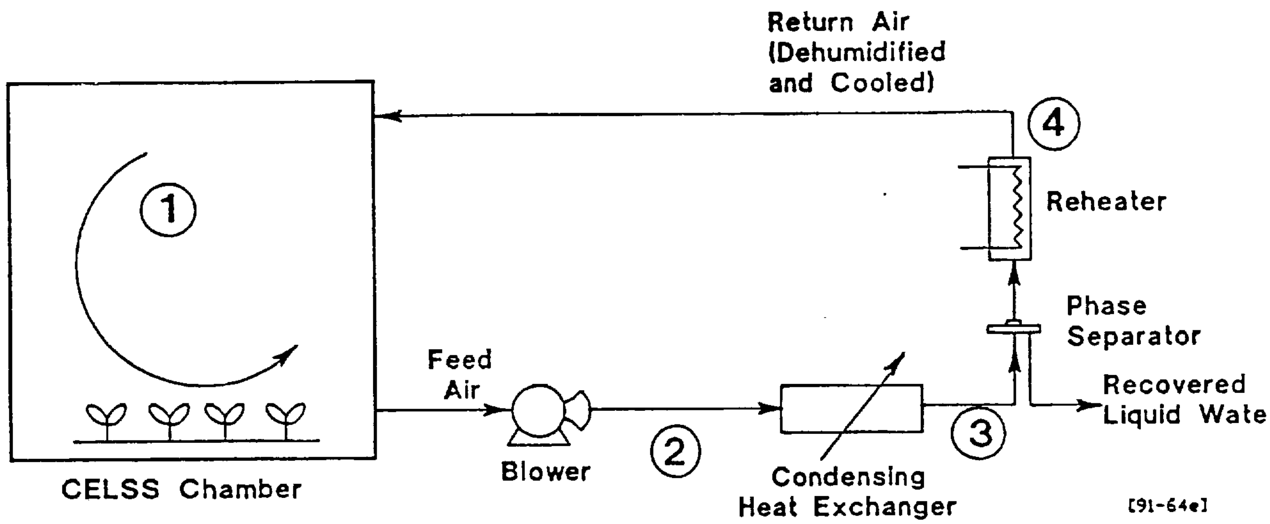

Figure 5. Schematic for "Conventional" System Controlling Temperature and Humidity in CELSS

Table I. State Points for Figures 5 and 6

State Point	Temperature				Flow Rates	
	Dry-Bulb		Dew-Point		Air (L/min)	Water Vapor (L/min)
	(°C)	(°F)	(°C)	(°F)		
1	25	77	17	63	---	--
2	25	77	17	63	4500	86
3	16	62	16	62	4500	84
4	23	74	16	62	4500	

<u>System Specifications</u>
- 200 watts from lights
- 550 watts from heaters
- 160 gm/hr of recovered water
- 1 m^2 growing area
- 4 mmHg pressure drop through WRHE module
- 100 watts total for blowers

This subsystem, while functional, has key problems. First, the use of condensing heat exchanger results in liquid water being in contact with the air stream. This presents a potential environment for the growth of various microbes. Such microbes could pose health hazards for the astronauts and for the plants, and also can ultimately cause biofouling of the heat exchanger and/or the phase separator (Blackwell et al., 1991).

The second problem stems from the inherent variability of the plants in these CELSS chambers. Design of the heat- and water-removal subsystem is straightforward for the case of a steady-state plant chamber with no variation in the transpiration rate or energy (lighting) inputs. In this unrealistic case, it is possible to design a condensing heat exchanger that cools a certain flow of air to the dry-bulb and dew-point temperatures that correspond to the required heat- and water-removal rates.

However, any variation in energy input (lights) or water-vapor input (transpiration) would result in this condensing heat exchanger removing too much heat or too much water vapor for the new conditions. Given that the condensing heat exchanger is of a set size, the system designer cannot provide the subsystem variation needed to respond to this changed baseline without a reheater capability. In addition, conventional environmental-control subsystems also require a rehumidifying capability (steam injection, for example) as well.

Figure 6 shows this conventional situation plotted on a psychrometric chart, with the circled numbers on the chart corresponding to the state points in Figure 5. From State Points 2 to 3 in this example, the air passes through the condensing heat exchanger, where it is cooled to the dew point and then continuously cooled. Water condenses, is removed by the phase separator, and the air enters the reheater and is brought to the conditions shown by State Point 4. This reheating step results in an energy input that substantially increases the energy requirement of the subsystem. The membrane-based technology under development in this program eliminates this need for costly reheating of the circulating air.

The third disadvantage inherent to any condensing heat-exchanger technology is the need for a phase-separation device. A phase separator is needed to remove the condensed water--likely in suspended droplets--from the air stream. This technology is complicated and energy-intensive, as is discussed below.

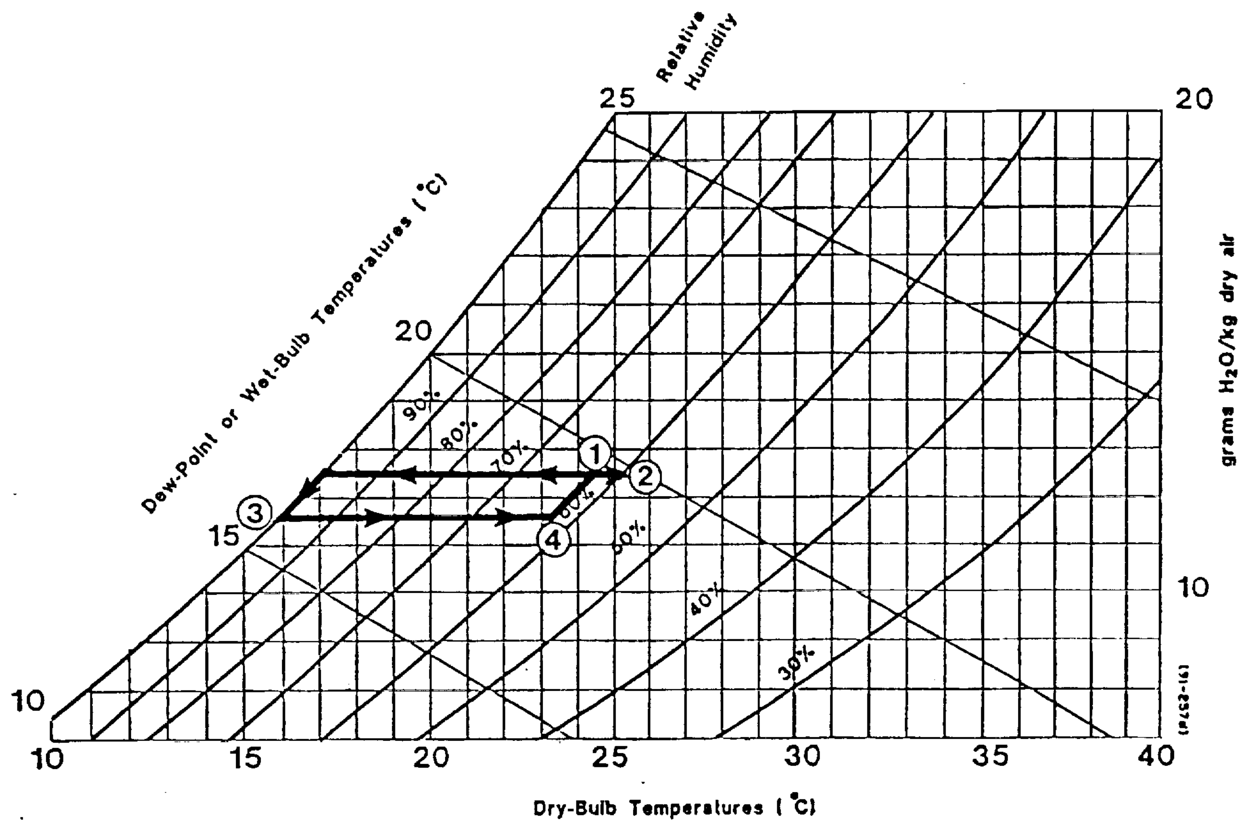

Figure 6. Representation of Air-Stream State Change Through Chambers for Conventional CELSS

II.B.2. Conventional Water-Removal Devices

Figure 7 shows a schematic of one phase separator (known as the water separator) under development for NASA. As the figure shows, this technology is based on a rotating element. As the water-droplet-laden air enters the device, the rotation causes the water droplets to be flung to the outer surface of the element. There, they are collected by a pitot tube and removed from the system as a liquid water stream.

This process has potential to perform the task of water-droplet removal from air streams in microgravity. However, NASA personnel have raised concerns regarding this type of design. First, a rotating device such as this has, by necessity, several rotating seals and bearings. These offer potential for failure--especially in the presence of liquid water.

Second, the device results in direct contact between liquid water and the air stream. As was mentioned above, this can

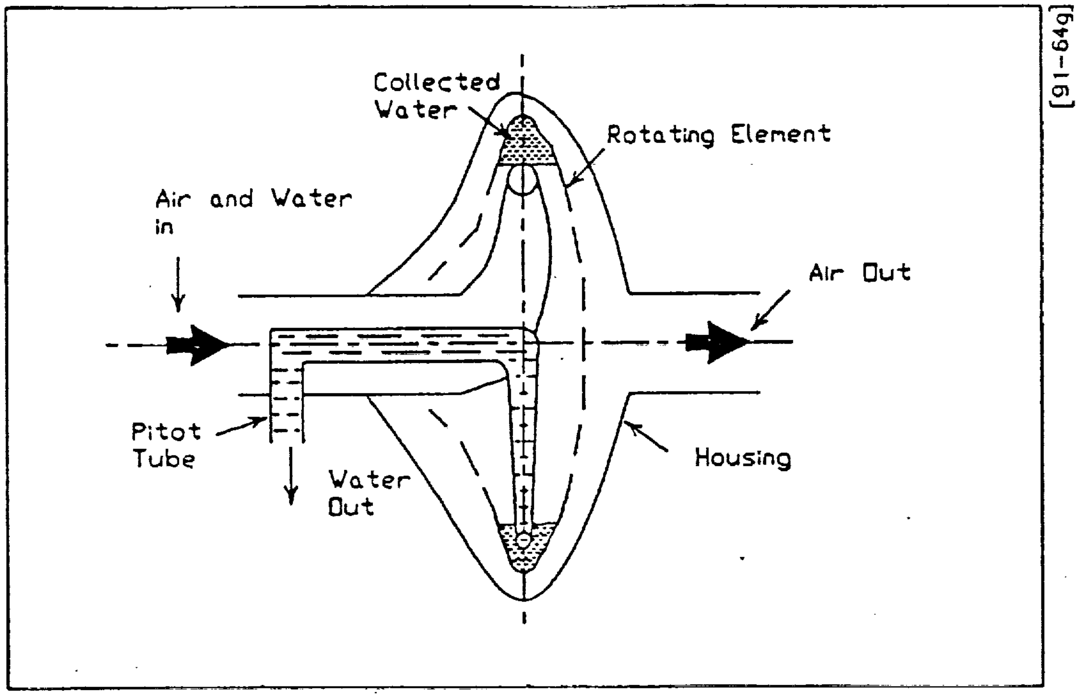

Figure 7. Schematic Representation of the Water Separator (Blackwell et al., 1991).

provide an opportunity for microbial growth with associated health hazards. Furthermore, fouling of the various orifices, tubes, seals, and channels with this biological growth--or other contaminants--may well be a problem.

These potential drawbacks have resulted in the following problem statement from NASA personnel (Blackwell et al., 1991):

> "The problem is to design the minimum cost (to be defined) transpiration-water-recovery system which will, when supplied with an airflow stream which contains water vapor, deliver (1) an airflow stream containing no liquid water and less water vapor than that entering, and (2) a liquid water flow stream containing no gas phase and which is not saturated with dissolved gases."

As will be shown in the following sections, the technology under development in this program preliminarily meets these criteria.

III. RESULTS AND DISCUSSION

The overall goal of the Phase I program was to study the feasibility of a membrane-based subsystem for 1) the recovery, purification, and reuse of water vapor; and 2) the removal of heat from a CELSS chamber. Specifically, our goals as stated in the Phase I proposal were as follows:

1) to fabricate dehumidification modules appropriate for this application;

2) to study the performance of these dehumidification modules on a range of air streams simulating the conditions in CELSS chambers;

3) to fabricate membrane contactors appropriate for this application;

4) to study performance of membrane contactors over a range of liquid-water flow rates, temperatures, and forced-air convection rates, simulating possible design conditions of CELSS chambers;

5) to gather available data on operation or expected operation of CELSS chambers that exist or are in the design phase;

6) to incorporate the above information into our model; and

7) to design systems for CELSS chambers selected in consultation with NASA personnel, and to evaluate the utility of this approach.

We successfully accomplished all of these goals during the Phase I program. Moreover, the first-generation technology for dehumidification was delivered to ARC for preliminary testing. The feedback from ARC personnel was that this system was too complicated and bulky.* We then conceived of new technology for the dehumidification step--technology that turned out to be a new and effective way to perform water-vapor or water-droplet separations from air in weightless environments.

In this section, we first describe the final subsystem developed during Phase I for environmental control in PGCs. In this description we describe in detail the state of a theoretical packet of air through each stage of the subsystem. We then describe the operation of each of the technologies making up this subsystem and present laboratory data on their actual operation. This section concludes with a comparison of this subsystem and conventional technology designed for use in environmental control of PGCs.

III.A. SUBSYSTEM DESIGN FOR CELSS CHAMBERS

A schematic of the final membrane-based subsystem configuration conceived of in Phase I is shown in Figure 8. This subsystem is made up of the two basic technologies: 1) the membrane-contactor module operated as an evaporative cooler (the EVCR), and 2) second type of membrane contactor operated as a water-recovery heat exchanger (the WRHE). The psychrometric chart in Figure 9 summarizes the thermodynamic pathway of a complete cycle through the PGC and through the components of the subsystem. Table II summarizes the state points called out in Figures 8 and 9.

In following a theoretical packet of air through this subsystem, we begin at State Point 1, as shown in Figure 8. The conditions in Table II for State Point 1 correspond to the desired conditions for that zone of this two-section plant chamber. The primary energy input to this chamber zone is from the required growth lights. The temperature rise of the air as it transits this chamber is kept low in part by the transpiration of water vapor by the plants.

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* A summary of the Phase I studies of this vacuum-driven technology can be found in Appendix A.

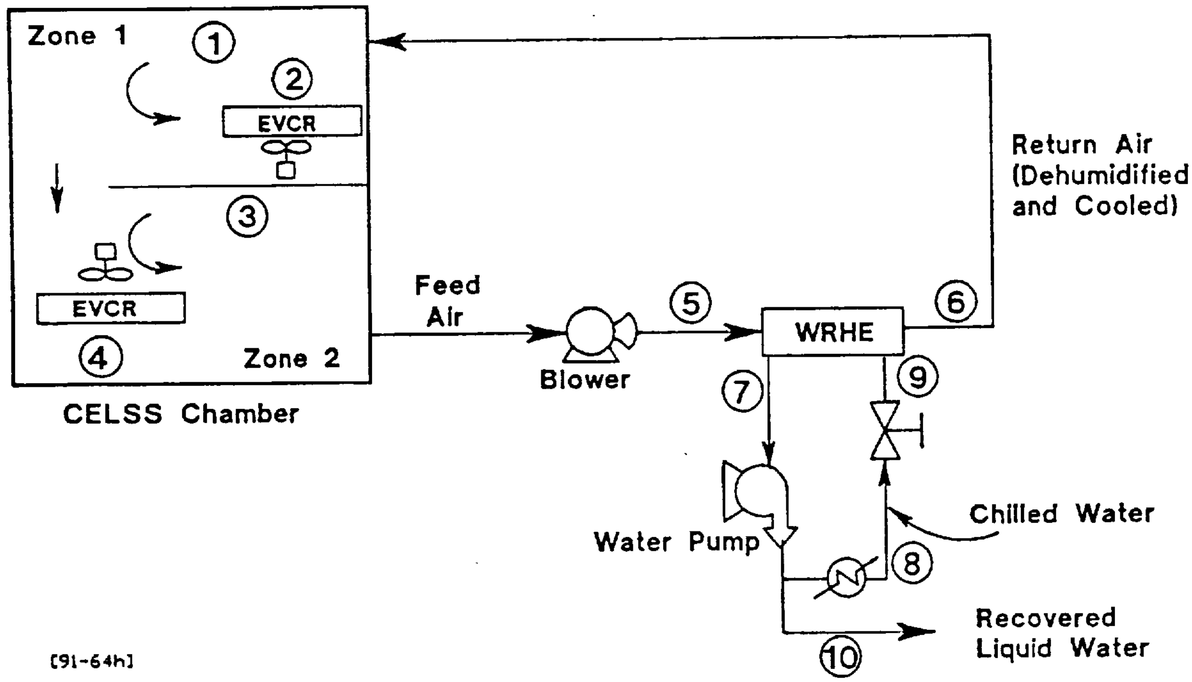


Figure 8. Membrane-Based Subsystem for Temperature and Humidity Control

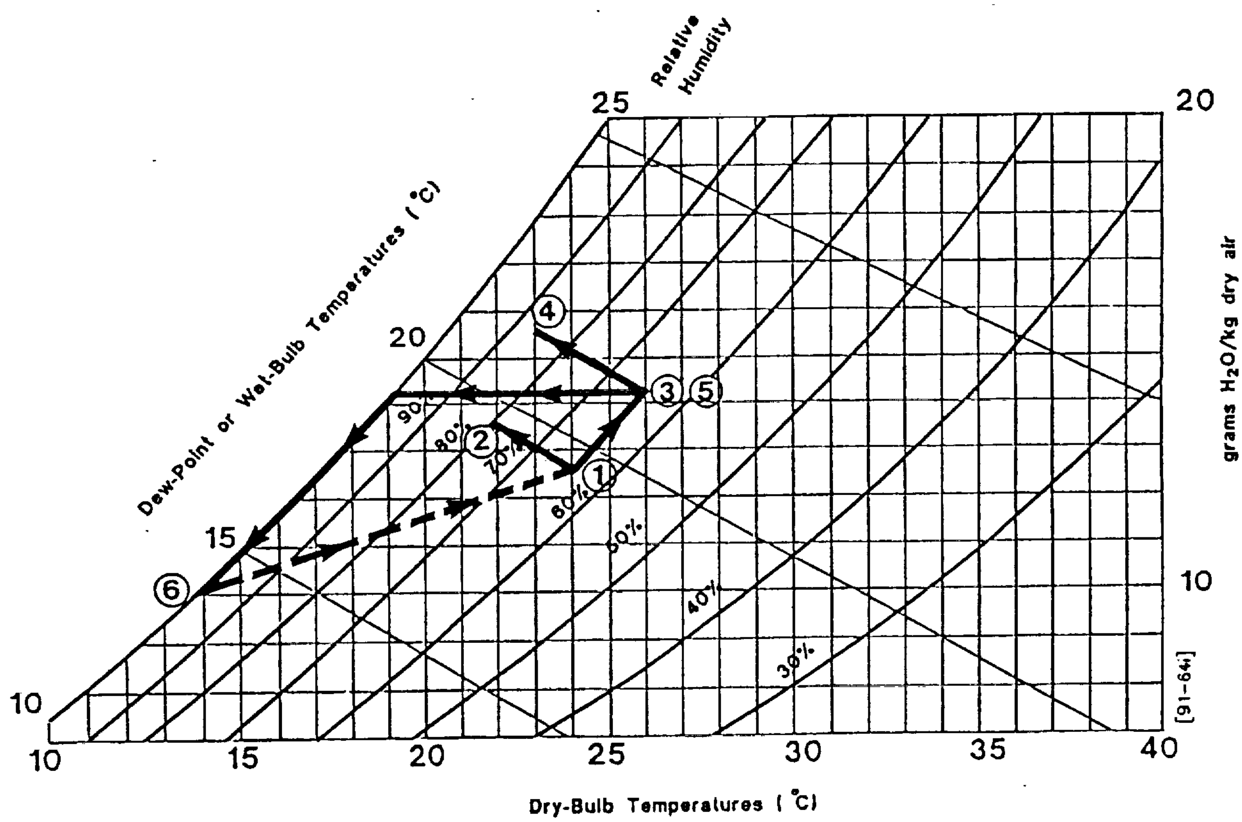


Figure 9. Representation of Complete Cycles of Air-Stream State Change for BRI Membrane-Based Subsystem

Table II. State Points for Figures 8 and 9

State Point	Temperature				Relative Humidity (%)	Flow Rates	
	Dry-Bulb		Dew-Point			Air (L/min)	Water (L/min)
	(°C)	(°F)	(°C)	(°F)			
1	24	75	16	61	61	--	
2	22	71	18	64	79	967	
3	25	77	19	66	69	--	
4	23	73	20	68	84	1699	
5	25	77	19	66	69	550	
6	14	57	14	57	100	550	
7	7.1	45					1500
8	7.1	45					1500
9	5.0	41					1500
10	5.0	41					160

System Specifications
- 200 watts from lights
- 1 m^2 growing area
- 160 gm/hr recovered water
- 80 gm/hr water evaporated by EVCR #1
- 80 gm/hr water evaporated by EVCR #2
- 4 mmHg pressure drop through WRHE module
- 2 mmHg pressure drop through EVCR modules
- 12 watts for WRHE blower
- 28 watts for EVCR blowers
- 40 watts total for blowers

To complete the control of the temperature rise across the chamber zone, a slip stream of air from the chamber is directed through the EVCR by a blower; water is evaporated into the slip stream, raising the humidity and lowering the dry-bulb temperature. Enough water is evaporated in the EVCR to keep the total amount of water-vapor input to the chamber constant--whatever the rate of transpiration by the plants.* This results in the temperature rise across the chamber being kept at the set-point value (i.e., the difference in dry-bulb temperature between State Points 1 and 3). This slip stream is then mixed with the bulk air circulating in the chamber zone.

* A discussion of how this rate of evaporation is controlled is presented in Section III.D.

(Mixing of air streams is represented by dashed line on psychrometric chart.) The flow rate of the air slip stream to the EVCR, and thus the evaporation rate and temperature drop, is controlled by process-control logic, which is discussed later. The psychrometric chart in Figure 10 shows the thermodynamics of the EVCR and of this zone's conditions.

Figure 11 summarizes similar information for the other zone of this two-zone PGC. A key advantage to this membrane-based subsystem is its ability to operate in zones of a given PGC with differing conditions. This allows optimal growth conditions for various plants, or parts of a given plant's life cycle, to be maintained in the same chamber. State Points 1 and 3 in Table II illustrate this point.

At State Point 5 (see Figure 8), an air stream is pulled from the chamber and fed into the WRHE. Here, water vapor is pulled from the air stream, across the hollow fibers in the WRHE,

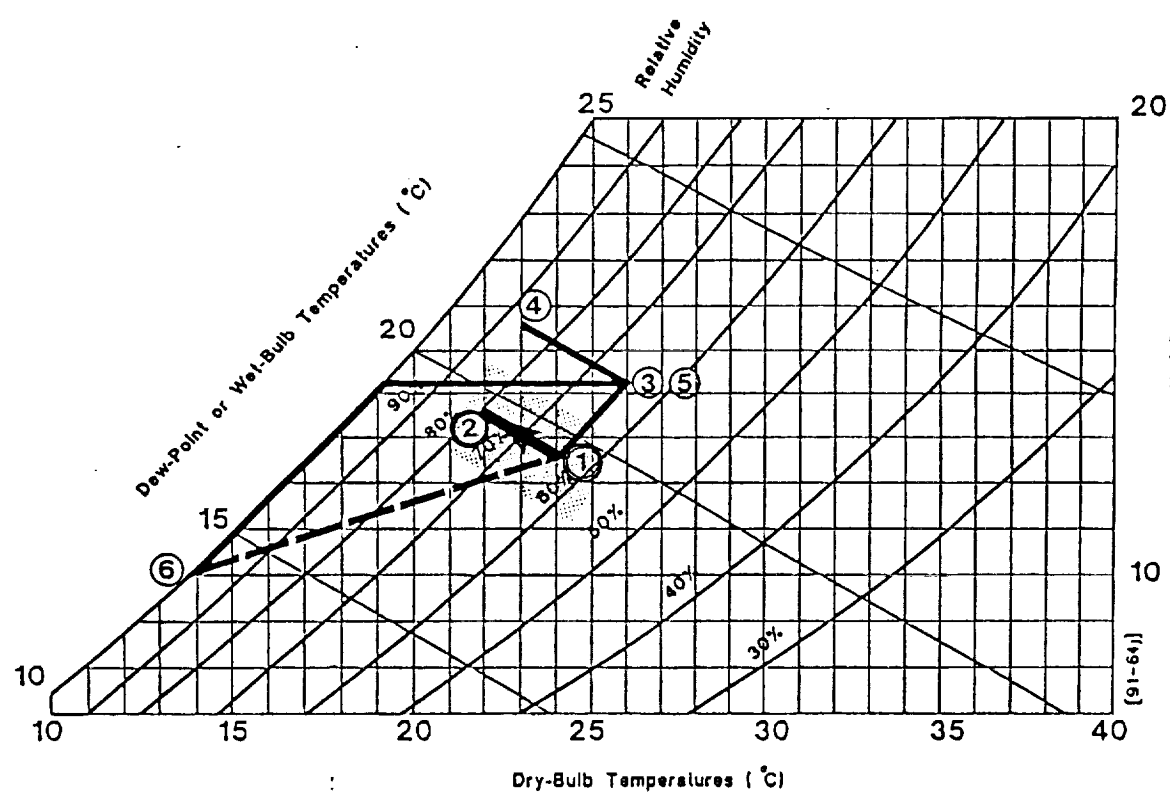


Figure 10. Representation of the Change of the Air-Stream State as It Passes through the First EVCR (Shaded Area) in the BRI Membrane-Based Subsystem

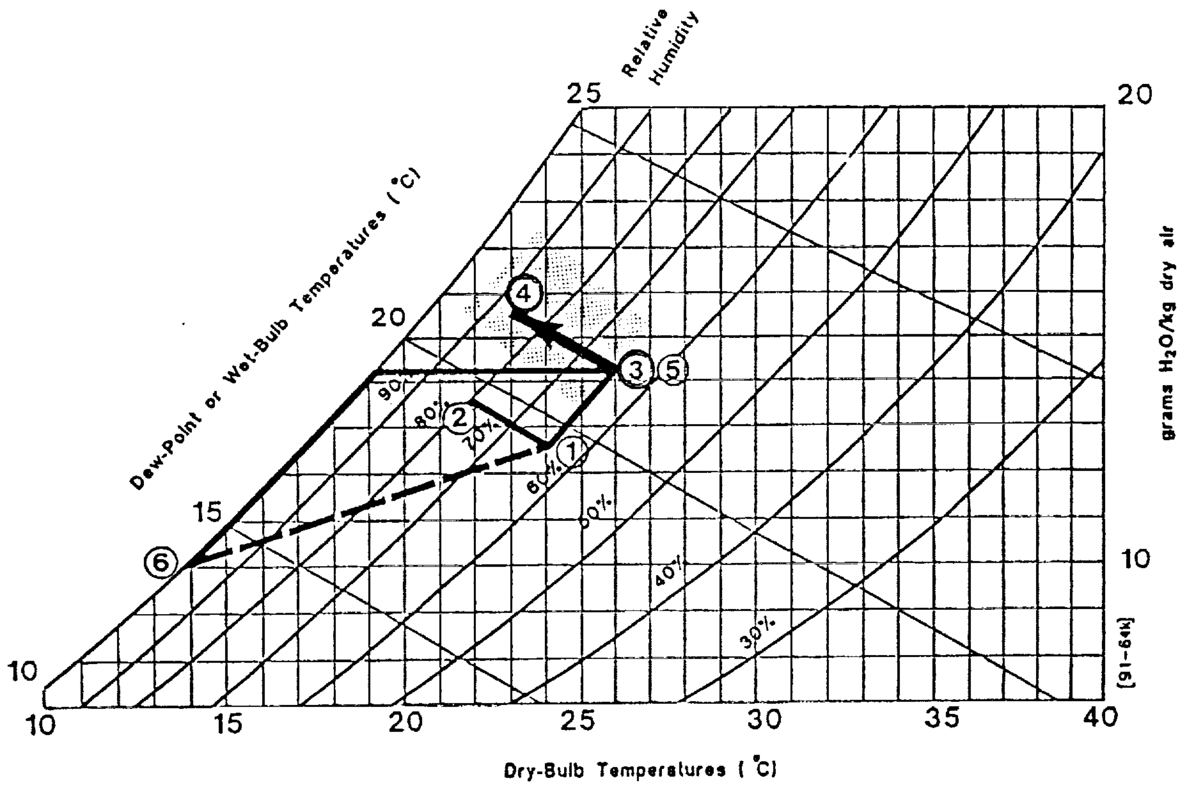


Figure 11. Representation of the Change of the Air-Stream State as it Passes through the Second EVCR (Shaded Area) in the BRI Membrane-Based Subsystem

and into a chilled liquid-water stream being fed down the lumens of the hollow fibers (see Figure 2). As is shown by the psychrometric chart in Figure 12 and State Points 5 and 6 in Table II, the dry-bulb temperature and the dew-point temperature of this air stream are lowered. This stream is then fed back into the first zone of the PGC as shown in Figure 8. There is no need for a phase separator or a reheating step.

(As required by NASA rules, all proprietary information is extracted from the main body of the text.) See Proprietary Addendum Item #1, Page 61.

Another key advantage of this subsystem is inherent in the methods used for its process-control logic. A major goal in developing this technology was to avoid the need for complicated humidity sensors or other sensing devices. The system shown in Figure 8 requires only two conventional thermocouples to sense dry-bulb temperatures. This simple measurement, and on/off or

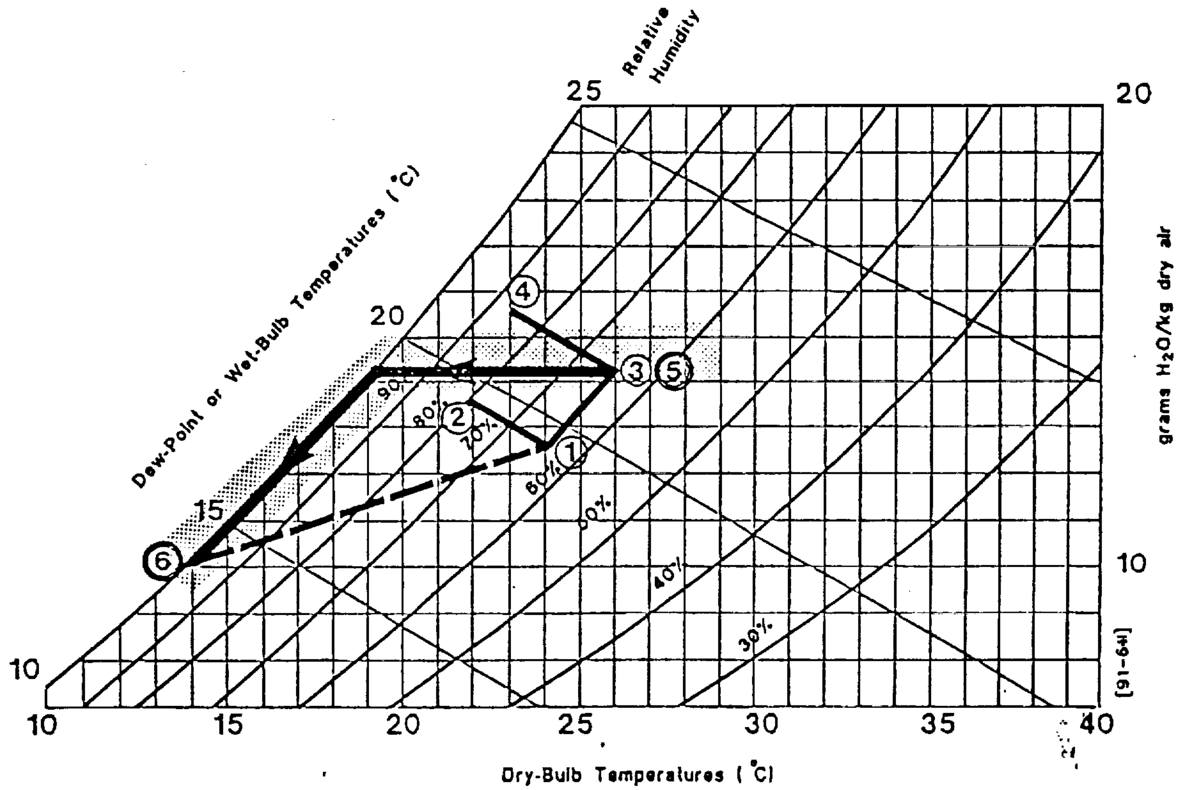


Figure 12. Representation of the Change of the Air-Stream State as it Passes through the WRHE (Shaded Area) in the BRI Membrane-Based Subsystem

variable-speed switching of the blower motors, is sufficient to control the environment of PGCs under a wide variety of conditions. The details of the process-control logic will be discussed in the sections to follow.

To summarize, the advantages of this membrane-based system for CELSS environmental control are as follows:

1. The effective removal of water vapor or water droplets from air--in a micro- or low-gravity environment.
2. A highly energy-efficient thermodynamic cycle--i.e., no reheating required.
3. Simple, lightweight, hollow-fiber membrane-module components with a minimum of moving parts.
4. Simple process-control logic, including simplified control-variable measurement.

5. The potential for providing several plant-growth zones with differing conditions--allowing for optimal conditions for plant growth.
6. The use of water as the "thermodynamic working fluid." This allows the recovery and reuse of water from the PGC and avoids the use of a potentially troublesome conventional working fluid.
7. Minimal need for "high grade" energy--i.e., the subsystem uses only small amounts of electricity to operate fans or blowers and does not require the use of any extreme temperature sources or sinks.
8. A subsystem design that accommodates large swings in transpiration of water vapor--i.e., it can maintain the desired conditions in the PGCs despite large swings in plant transpiration rates (for example, the two-week swings between lunar day and night, the difference between new and mature crops, or the potential situation of partial or complete crop failure).

III.B. WATER-RECOVERY HEAT EXCHANGER (WRHE)

The purpose of the WRHE is to remove the bulk of the heat and water vapor from a given CELSS chamber to control the chamber conditions as desired. Furthermore, NASA needs a simple and efficient technology that can remove water vapor from the air streams in microgravity environments--and the WRHE serves that purpose.

III.B.1. Physical Situation

Figure 13a shows a schematic of the WRHE portion of the subsystem. **See Proprietary Addendum Item #2, Page 61.** Figure 13b shows the typical temperature profile of the air stream as it passes through the module. Note that the dry-bulb temperature quickly decreases to the dew-point temperature as sensible heat is removed from the air. Once the air stream is at the dew-point temperature, water vapor starts to condense, resulting in a reduction in dew-point and dry-bulb temperatures.

a)

b)

c)

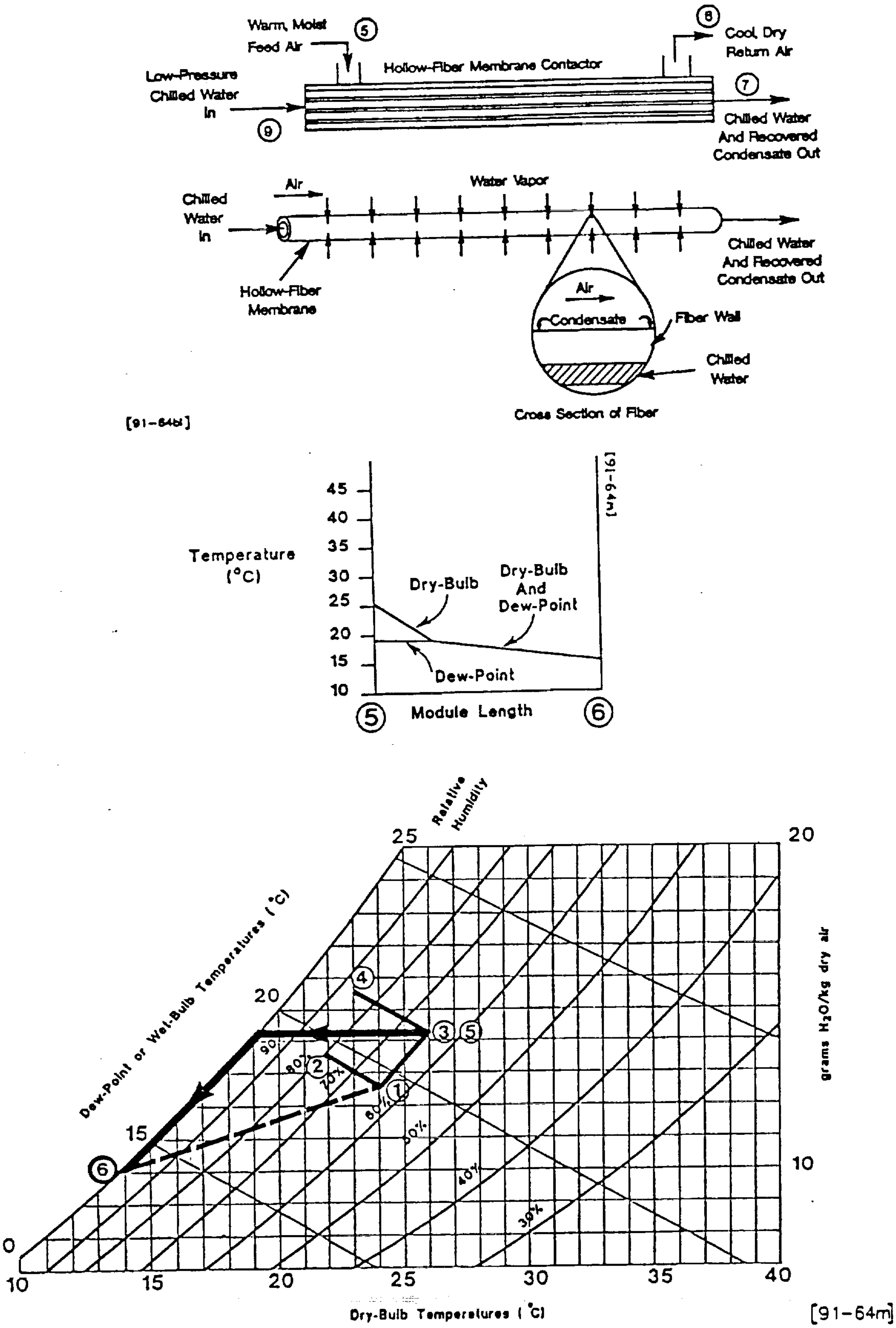


Figure 13. Summary of the WRHE in the BRI Membrane-Based Subsystem

The psychrometric chart showing the typical conditions of this air stream is shown in Figure 13c.

To demonstrate the feasibility of this approach in the Phase I program, we simply used a conventional regenerated-cellulose kidney-dialysis module that contains 1 m^2 of hollow-fiber membrane area. A photo of this module is shown as Figure 14, and a scanning electron micrograph (SEM) of the hollow fibers in the module is shown as Figure 15. We operated the module on the experimental setup shown in Figure 16. In this apparatus, air at a controlled temperature and dew point is fed to the shell side of the kidney-dialysis module, as shown in Figure 13a (i.e., down the outside of the hollow fibers). Chilled water is passed down the lumen side (i.e., inside) of the hollow fibers. As air and water vapor or water droplets enter the shell side of the module and contact the fiber bundle, three factors cause this water to pass through the membrane and into the liquid-water stream in the fiber lumens without passing air into the water.

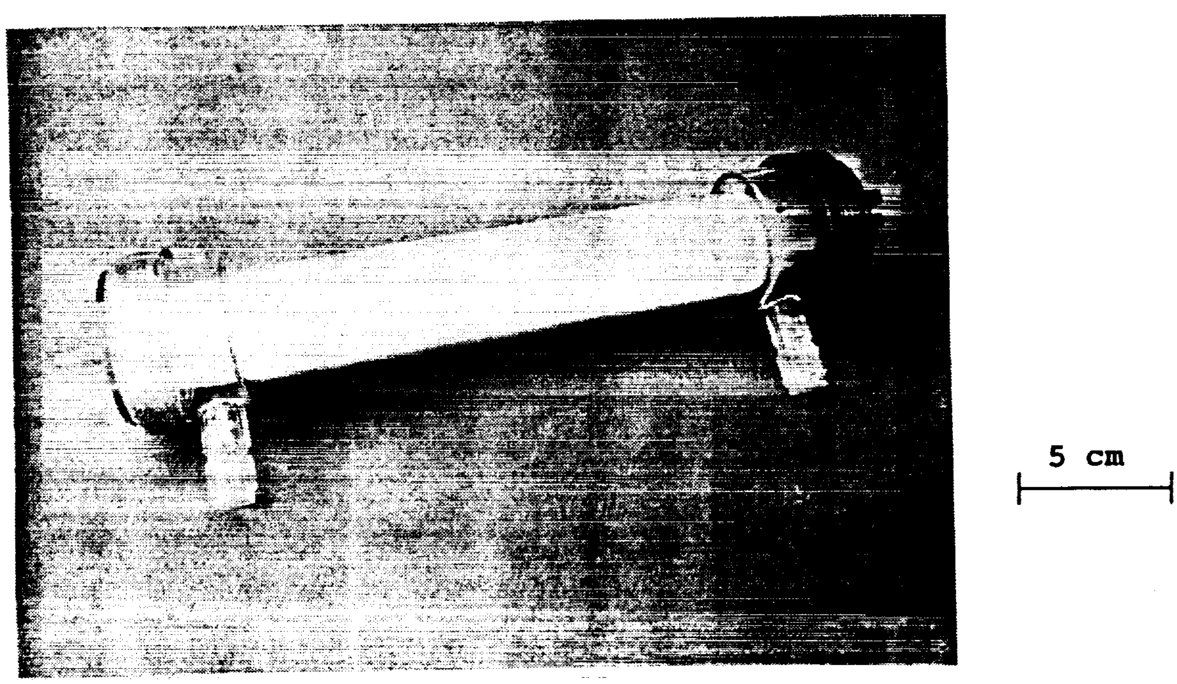


Figure 14. Kidney-Dialysis Module

Figure 15. SEM of Kidney-Dialysis Fiber

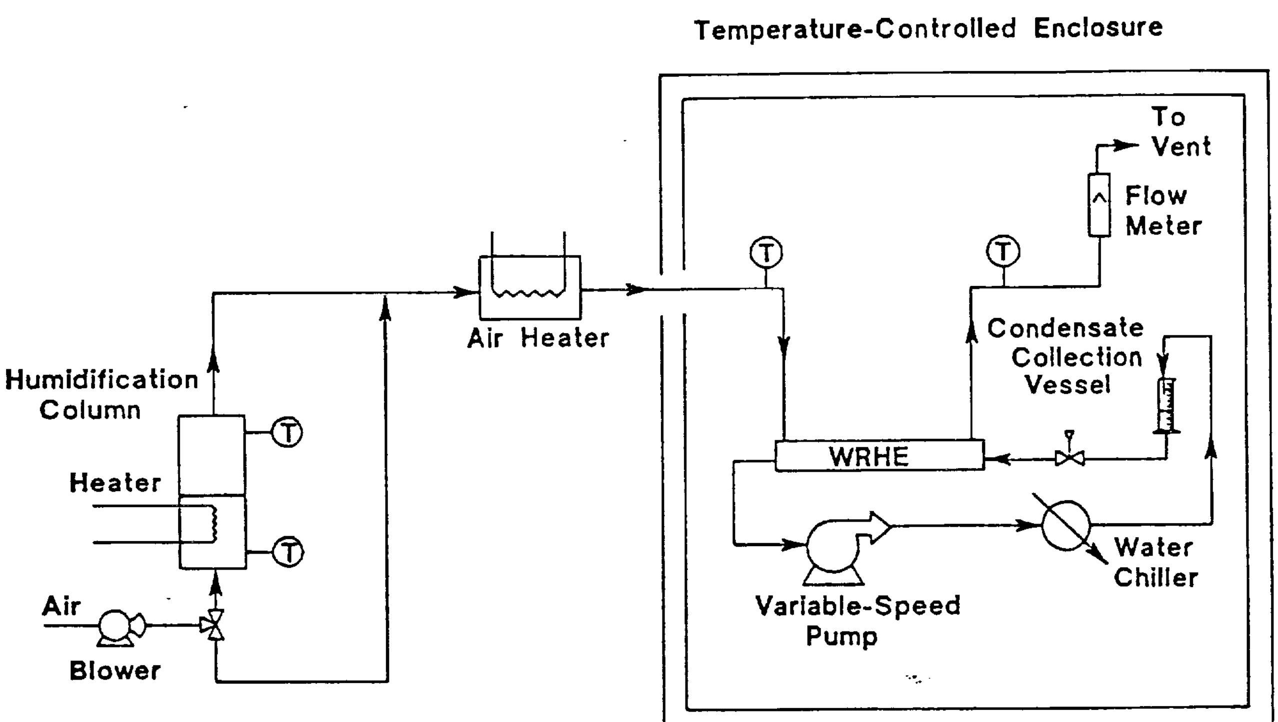


Figure 16. Apparatus for Testing WRHE

See Proprietary Addendum Item #3, Page 61.

Second, the liquid water in the fiber lumen is colder than the feed-air stream. This results in the fibers also being cooler than the air stream and causes the water to "condense" on the surface and then partition into the regenerated-cellulose fiber material. The rate of condensation of water vapor onto the fiber surface is described by the equation

$$C_w = \frac{(P^*_{in} - P^*_{out})}{P_T} \cdot V \cdot MW \cdot \frac{1}{22.4\ \text{L/mol}}, \tag{1}$$

where

C_w = rate of condensation (gm/hr),

P^*_{in} = partial pressure of water vapor in feed (atm),

P^*_{out} = partial pressure of water vapor in raffinate (atm),

P_T = total feed pressure (atm),

V = volumetric flow of feed air (L/hr at STP), and

MW = molecular weight of water (gm/mol).

The flow rate of water into the fiber lumens must be high enough to keep the temperature of the fiber surface on the shell side sufficiently low so as to result in a rate of condensation high enough for the device to be practical.

See Proprietary Addendum Item #4, Page 61.

Note that the hollow fiber serves to physically isolate the air stream from the liquid-water stream in the fiber lumen. This arrangement avoids the direct contact of air and liquid water and the associated problems. Furthermore, it allows the operation of this device in microgravity.

III.B.2. <u>Experimental Results</u>

We used the apparatus shown in Figure 16 to perform preliminary studies of the WRHE concept. Figure 17 (see **Proprietary Addendum Item #5, Page 63**) shows a summary of one experimental run, with the experimental conditions shown in the figure caption. As the figure shows, we were able to lower the dry-bulb temperature from 39°C to 10°C and the dew-point temperature from 22°C to 10°C. This corresponds to the removal of 52 watt-hr of energy and 31 gm of H_2O in each hour of operation. This, in turn, corresponds to an overall heat-transfer coefficient of 5 watts/m^2-°C and an overall mass-transfer coefficient of 40 gm H_2O/hr-m^2-atm. Under these conditions, then, it would take 380 m^2 of membrane area to remove the necessary heat and water vapor from a CELSS chamber sized for four crew members (Kliss, 1991). For completeness, the results of this experiment are shown on a psychrometric chart in Figure 18.

Figures 19 (see **Proprietary Addendum Item #6, Page 64**) and 20 show the results of another experimental run with a slightly different set of conditions. In each of these experimental runs, the clear module shell allowed us to observe the outside surface of the fiber bundle. There was no evidence of liquid water or fog formation on the shell side of the fibers. Furthermore, it was obvious that much of the feed-air stream was channelling

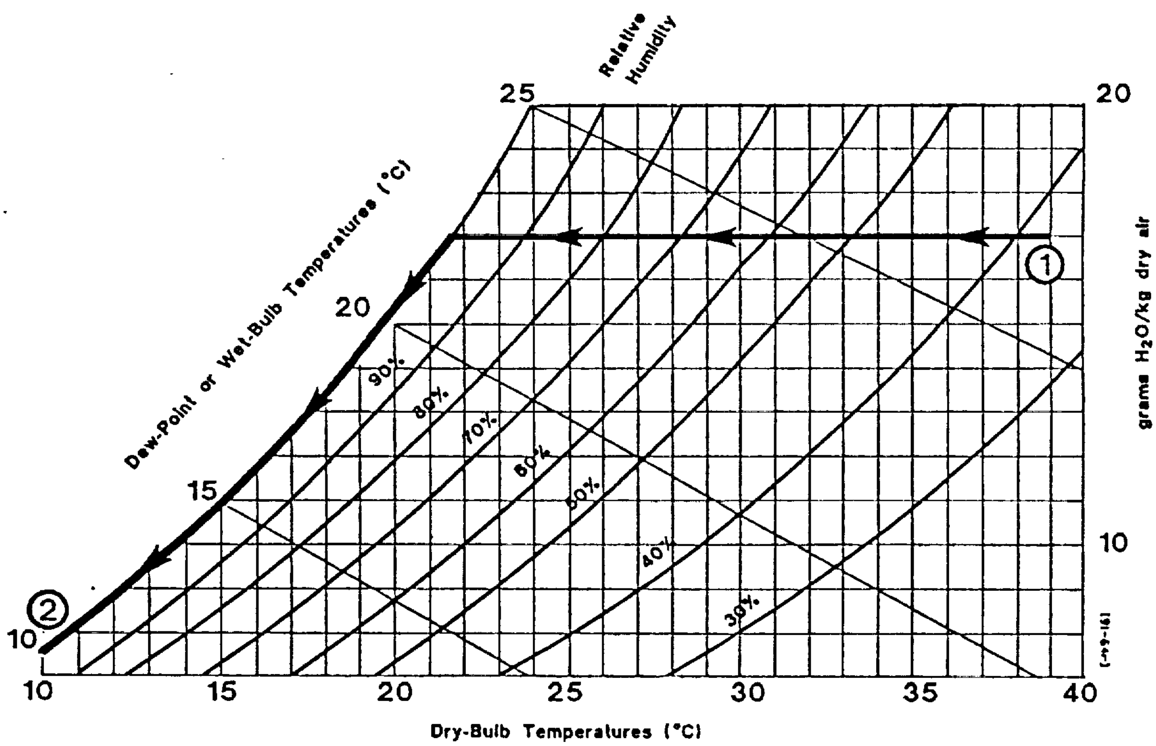


Figure 18. Representation of Change of the Air-Stream State for Figure 17

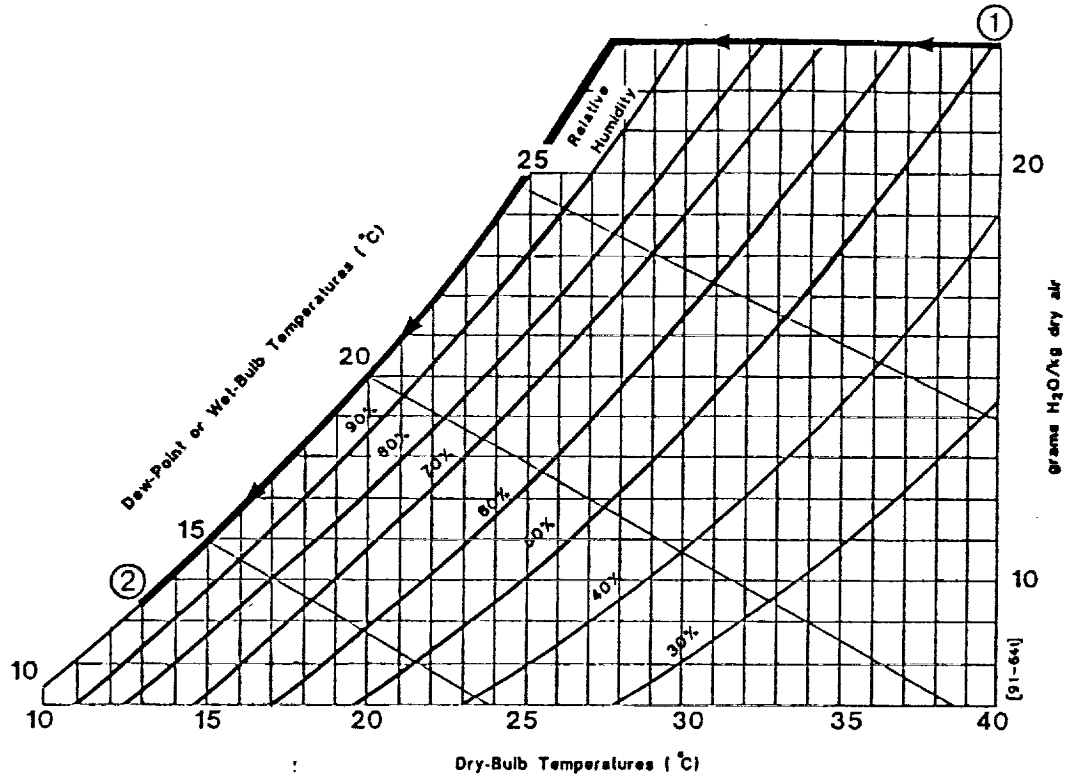


Figure 20. Representation of Change of the Air-Stream State for Figure 19

down one side of the module shell and therefore much of the available hollow-fiber area was not being used. This suggests that a more efficient module design that minimized pressure drop but maximized efficient contact of the feed-air stream with the fiber bundle will result in much higher heat- and mass-transfer coefficients and require less membrane area to perform a given heat- and mass-transfer duty.

An experimental run was performed to determine the upper limit of the overall heat-transfer coefficient attainable in a hollow-fiber WRHE. The module used contained only thirty fibers of a type used in a previous project for NASA to develop technology for spacecraft cabin dehumidification. SEMs of these microporous fibers are shown as Figure 21. **See Proprietary Addendum Item #7, Page 64.**

Figures 22 (**see Proprietary Addendum Item #8, Page 65**) and 23 show the data from this run. As Figure 22 shows, the overall heat-transfer coefficient was more than an order of magnitude

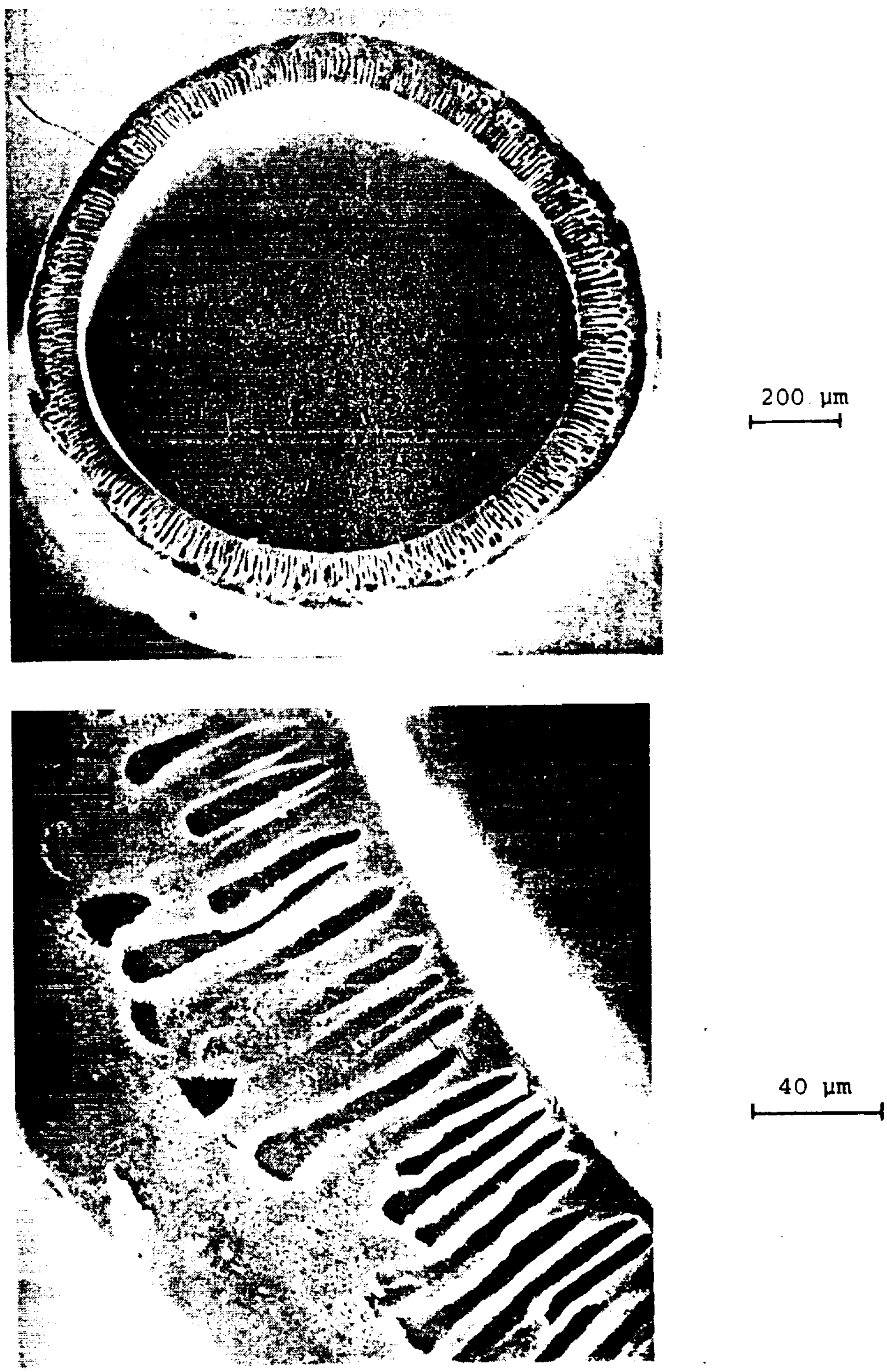


Figure 21. SEM of Polyethersulfone Fiber

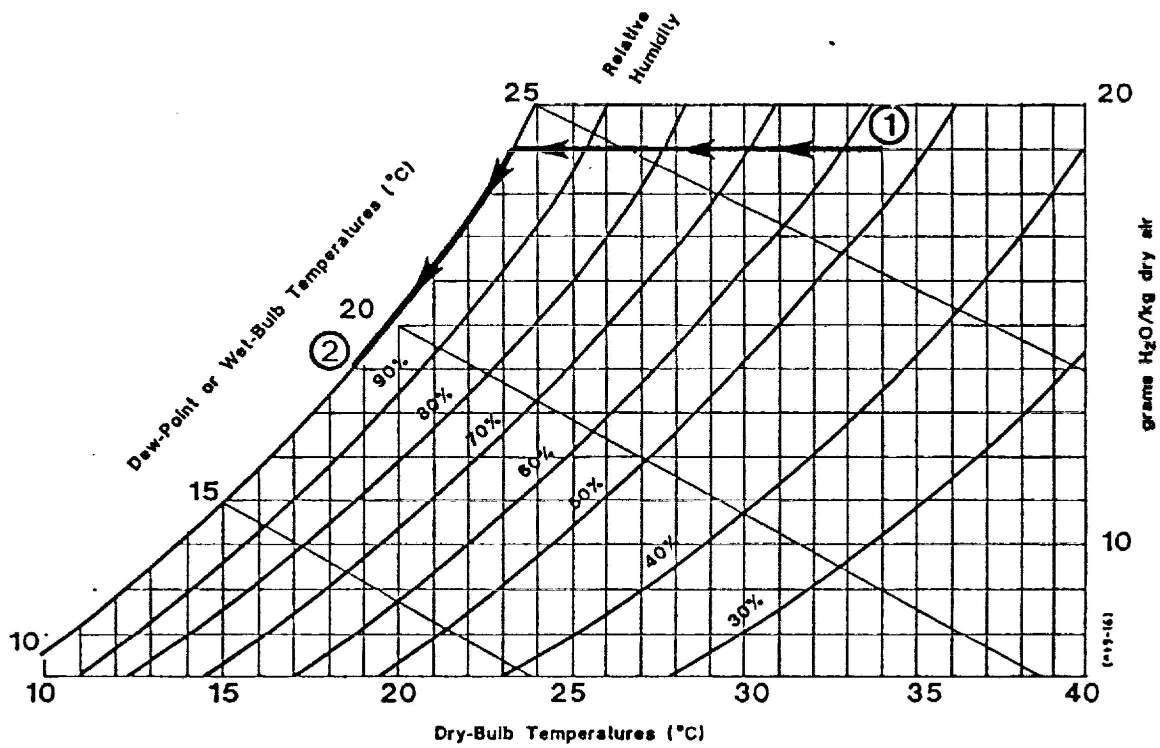


Figure 23. Representation of Change of the Air-Stream State for Figure 22

higher than that achieved with the commercial kidney-dialysis modules. This heat-transfer coefficient would correspond to a required membrane area of 21 m^2 for a four-person crew. This suggests that a module-development program in Phase II using fibers suited for this application would result in much more efficient transport characteristics and should lead to a very small membrane area being needed for the heat-transfer duty.

See Proprietary Addendum Item #9, Page 65.

Table III is a summary of the data taken from experimental runs using a kidney-dialysis module as a WRHE. The purpose of the experiments was to determine if the rate of condensation of water vapor as it was cooled below its dew point could be made to overwhelm the fibers' ability to recover the condensate. If the rate of condensation of water vapor overwhelms the fibers' ability to absorb the condensate, water droplets or fog would

Table III. Summary of Data and Calculated Values for WRHE Experimental Runs

	Feed-Air Temperature		Raffinate Air Temperature		Feed-Air Flow (L/min)	Water Recovered (gm/hr)	Energy Removed		Mass-Transfer Coefficient K_m, $\frac{gm}{hr\text{-}m^2\text{-}atm}$	Heat-Transfer Coefficient U, $\frac{watts}{m^2 \cdot K}$
	Dry-Bulb (°C)	Dew-Point (°C)	Dry-Bulb (°C)	Dew-Point (°C)			Sensible Heat (W)	Latent Heat (W)		
1	39	22	10	10	45	31	32	20	40	5.3
2	39	26	10	10	48	47	31	30	60	10
3	40	9	9	9	51	4	35	2	6	4.2
4	42	32	14	14	51	77	31	50	100	10
5	42	28	13	13	51	60	33	40	74	9
6	43	30	14	14	48	63	31	40	80	10

form. No fog or water droplets were observed during any experimental run.

In certain experiments, the module was operated in a regime of higher dry-bulb and dew-point temperatures (around 40°C and 32°C, respectively) than the upper range expected to be encountered in a PGC (35°C and 29°C, respectively). Even under these severe conditions, the module recovered all condensed water vapor.

For the Phase II program, substantial effort will be expended to choose the best fibers and to the best module design for this water-vapor and water-droplet application. This technology should have wide applicability within NASA for micro- and low-gravity environments, including extravehicular activity (EVA). Furthermore, we believe this technology has potential commercial application as well.

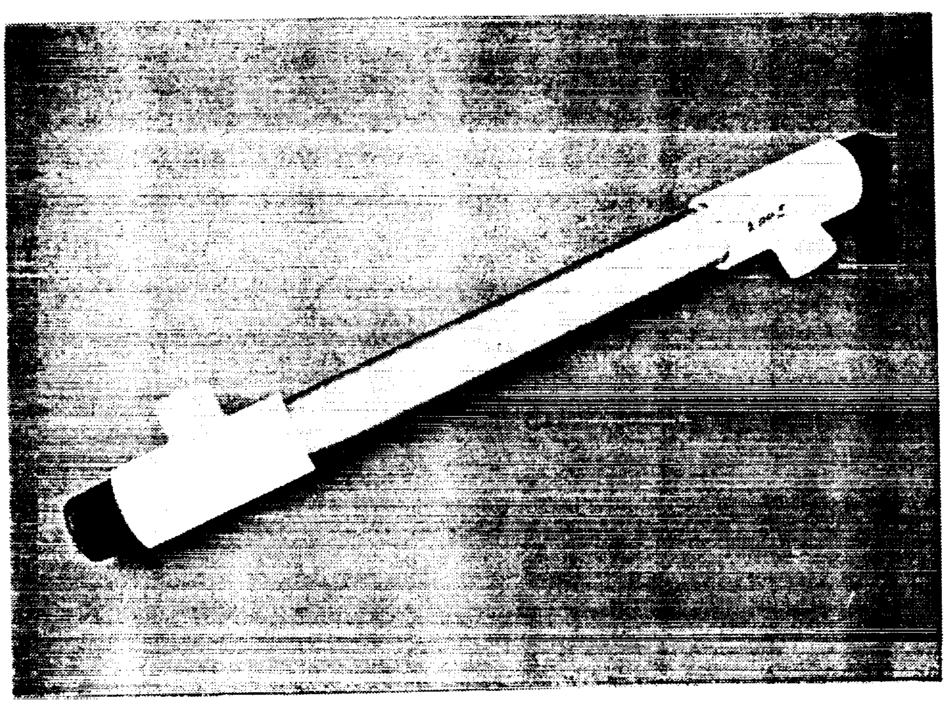
III.C. EVAPORATIVE COOLER (EVCR)

The EVCR was conceived to provide an alternative to the energy-inefficient reheating of the air stream as is done conventionally. Also, it is a far more efficient way to rehumidify, where necessary, than is steam injection, which uses high-quality energy to make the steam.

III.C.1. Physical Situation

Figure 3 shows a schematic of the EVCR. At the heart of this technology is a porous hollow-fiber membrane. In this case, the membrane is hydrophobic; i.e., under normal conditions water will not wet it.

A membrane-contactor module fabricated at BRI was used to study the feasibility of this approach. Figure 24 is a photograph of this module, and Figure 25 is an SEM of a hollow fiber used in the EVCR. This module was operated on the experimental apparatus shown in Figure 26. A reservoir of water was connected to the fiber lumens as shown. In this case, no pump is needed. An air stream is directed into the shell side of the module, contacts the bundle of fibers, and exits the module. As the expanded view in Figure 3 indicates, water vapor is evaporated from the water in the lumen, passes through the pores as vapor, and enters the air stream. As water evaporates,



5 cm

Figure 24. One of the Modules Used for EVCR

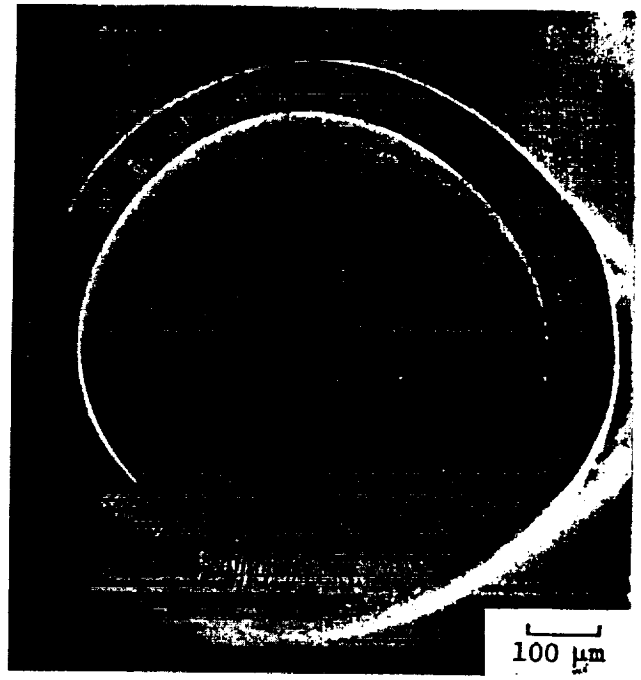


Figure 25. SEM of Porous Hollow Fiber Used for EVCR

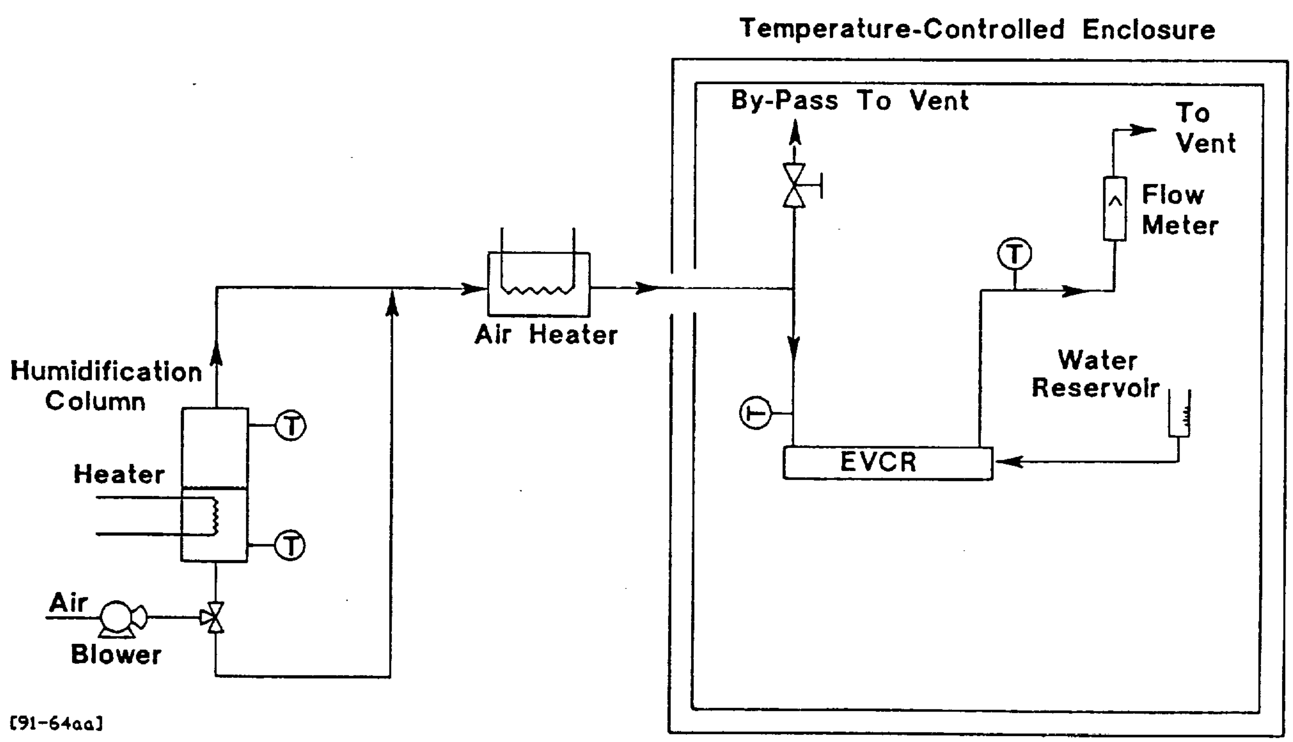


Figure 26. Experimental Apparatus for Testing the EVCR

additional water is drawn into the fiber lumens to replace it. There is no need for a water pump.

The driving force for water to evaporate here is simply the fact that the air stream is not saturated with water vapor. Hence, this technology operates much like a conventional evaporative air conditioner. However, here the membrane serves to isolate the liquid water from the air stream--i.e., there is no direct contact between the air stream and the liquid water. This allows operation in microgravity. And most importantly, there is no liquid-water phase in contact with the air stream to promote growth of bacteria or other microbes.

The energy necessary for evaporating the water into the vapor phase comes primarily from the air stream entering the module. Therefore, the air stream is cooled and humidified as it passes down the module. The process is likely limited by the transport of water vapor through the pores in the walls of the hydrophobic hollow-fiber membranes. This is described by the equation

$$J_v = k_m \cdot (P_f^* - P_s^*) \cdot A, \tag{3}$$

where

J_v = water-vapor flux (g/hr),

P_f^* = water-vapor pressure of feed air (atm), and

P_s^* = water-vapor pressure at wet-bulb temperature of feed air (atm).

The amount of cooling done on the air stream is, of course, directly related to this water-vapor flux and is described by

$$Q = J_v \cdot \lambda / A, \tag{4}$$

where

Q = heat transferred (watt/m^2) and

λ = latent heat of water (watt-hr/gm).

As with the WRHE, this technology operates as a balance between heat and mass transfer across the fiber wall. A good analogy for this technology is the conventional "sling psychrometer" used to determine relative humidity with a wetted-wick thermometer.

III.C.2. Experimental Results

We used the experimental apparatus shown in Figure 26 for our preliminary studies of this EVCR technology. Figure 27 shows an experimental result observed for the module at conditions specified in the figure caption. In this case, we were able to cool the air stream from a dry-bulb temperature of 27°C to 21°C. The dew-point temperature was raised from 13°C to 16°C. These results are plotted on a psychrometric chart in Figure 28 in the solid line from Points 1 to 2. This line approaches the wet-bulb curve along a line of constant enthalpy (since there is no energy input to the system). The dotted line that is a continuation of the solid line intersects the wet-bulb curve at the wet-bulb temperature of the feed stream. This intersection point at the wet-bulb temperature represents the performance of a module with no resistance to heat or mass transfer. Any point short of the wet-bulb point represents a module with finite resistance to mass and heat transfer. Hence, the closer the performance line approaches the wet-bulb point, the more efficient the module.

During Phase II work, EVCR module performance will be compared at baseline conditions. The module efficiency will be quantified with a math model. Figures 29, 30, 31, and 32 show the results of other experimental runs at other conditions.

Figure 33 is a summary plot of all the data presented above. This figure shows the effect on water-evaporation rate and the dry-bulb temperature of the air stream exiting the module as the flow rate of the air stream is varied. As the figure shows, increasing the feed-air flow rate increases the evaporation rate and the dry-bulb temperature of the exiting air stream--as expected. Again, this performance is the basis for the use of the speed of the feed-air blower as the primary process-control variable.

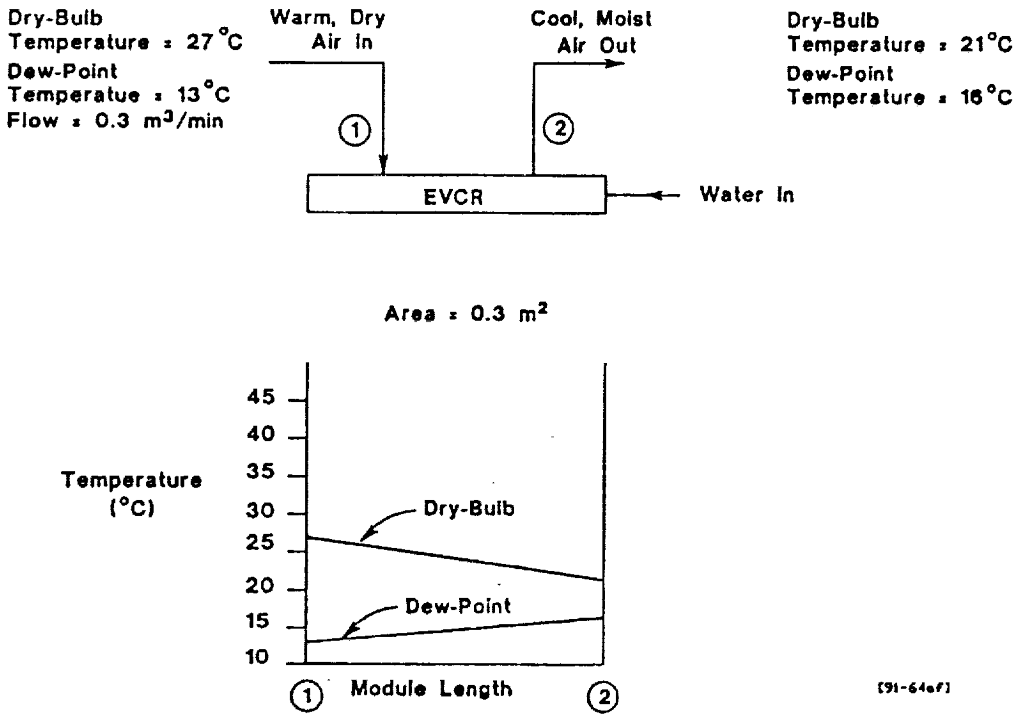


Figure 27. Summary of Experimental Run of EVCR at Conditions Listed Above

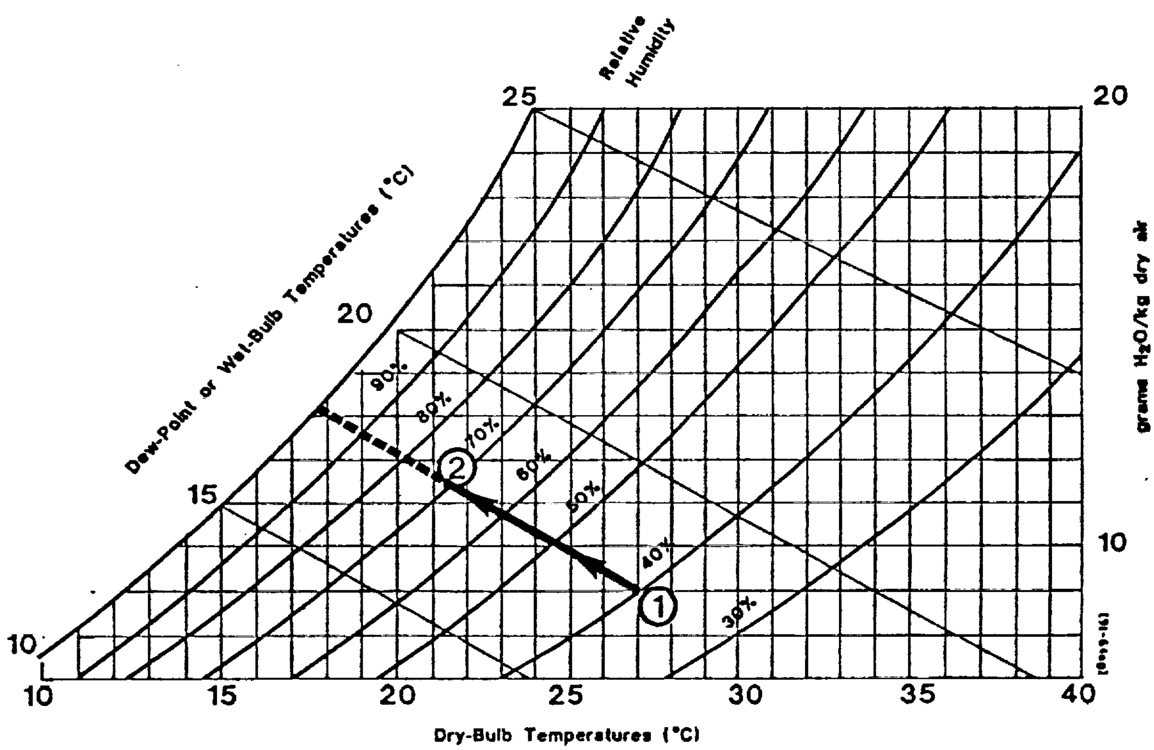


Figure 28. Representation of Change of Air-Stream State through EVCR for Figure 27

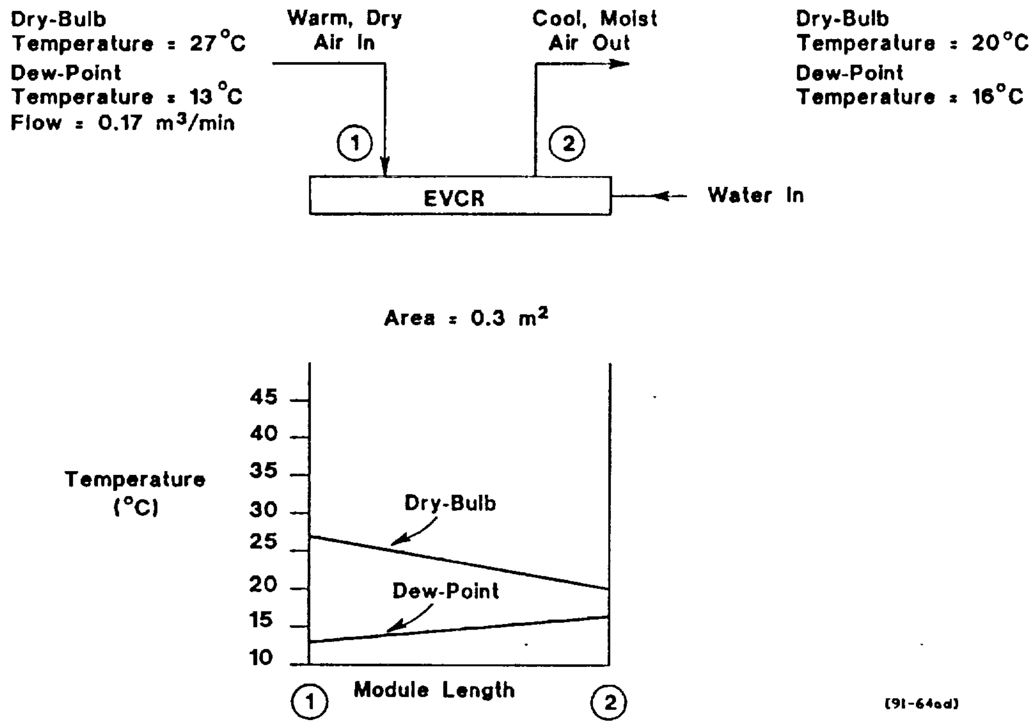


Figure 29. Summary of Experimental Run of EVCR at Conditions Listed Above

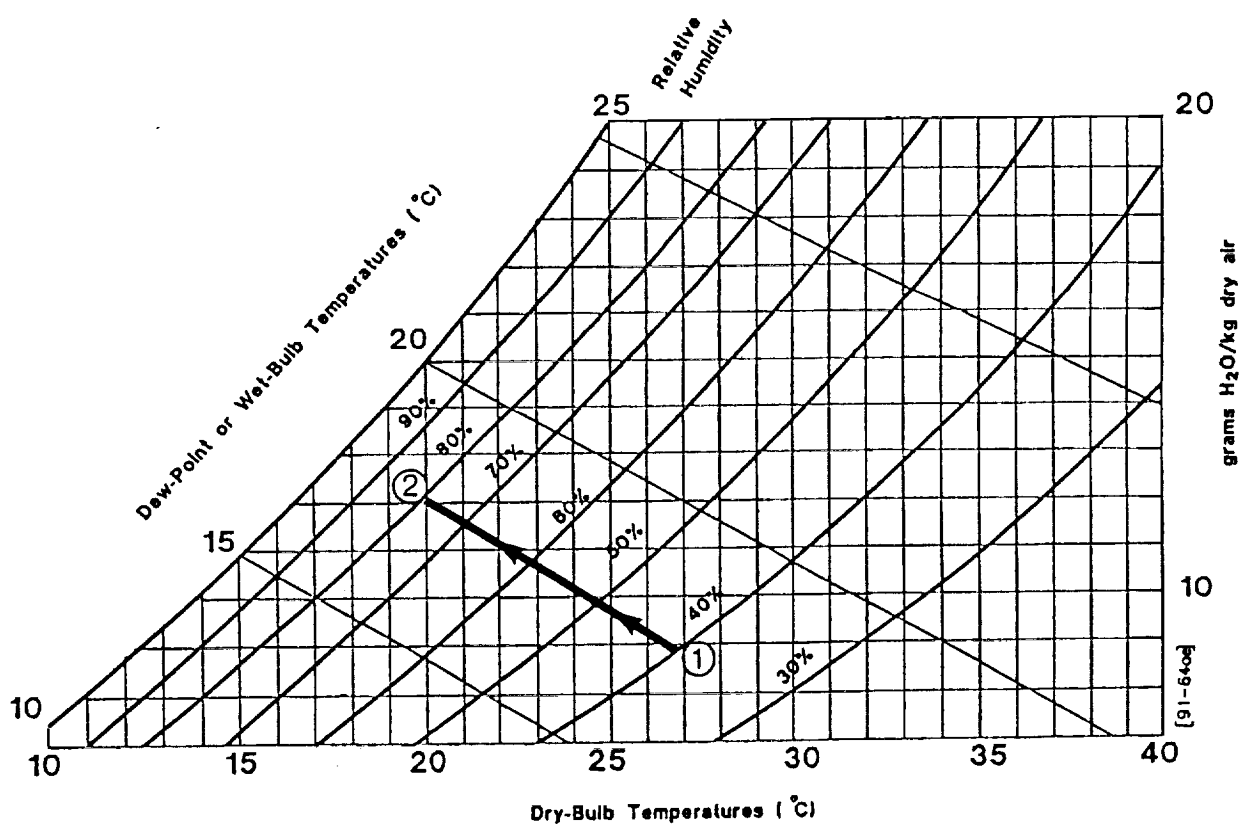


Figure 30. Representation of Changes of Air-Stream State through EVCR for Figure 29

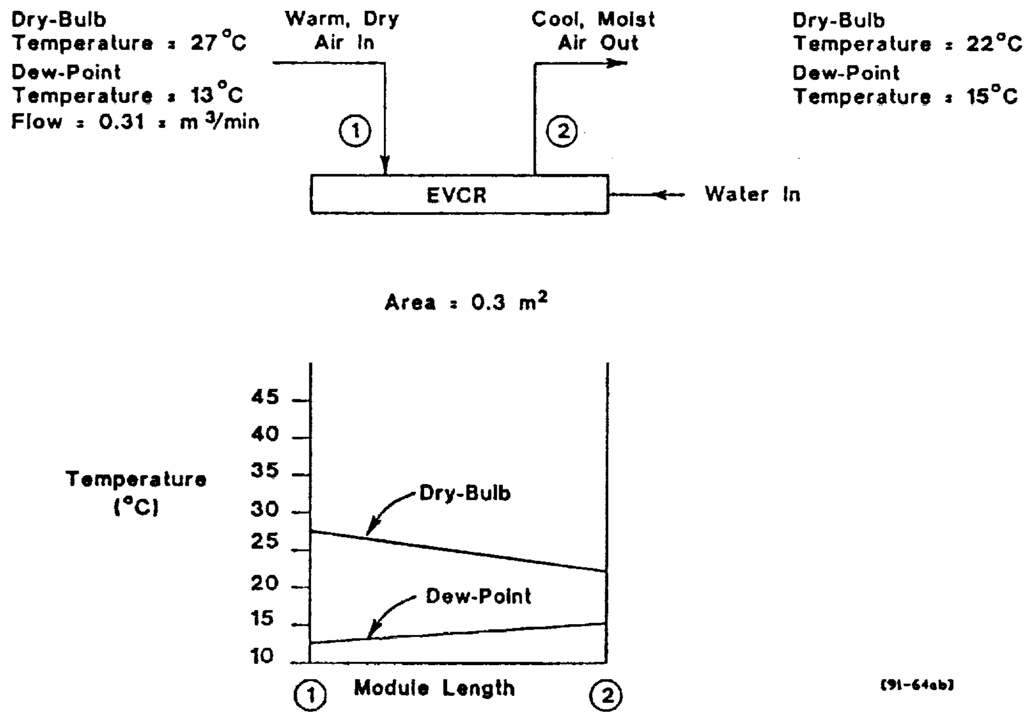


Figure 31. Summary of Experimental Run of EVCR at Conditions Listed Above

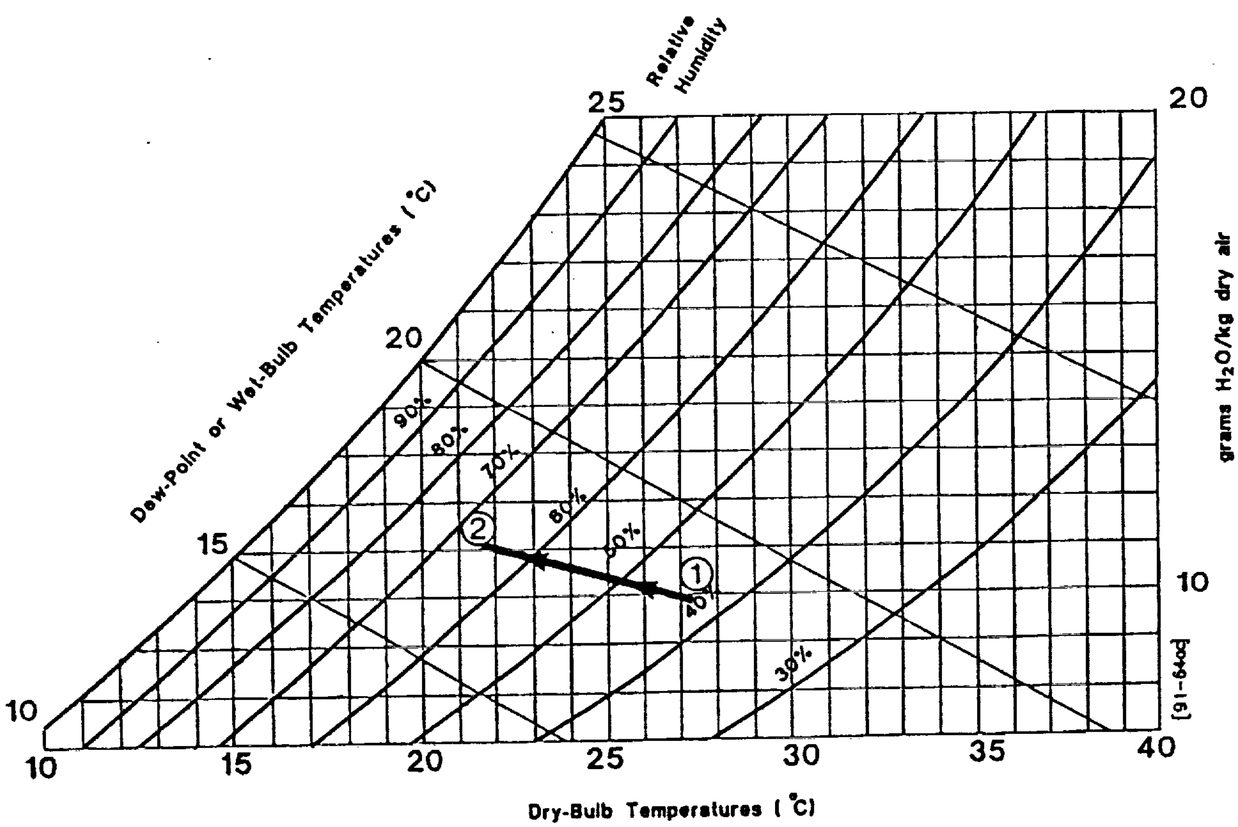


Figure 32. Representation of Change of Air-Stream State through EVCR for Figure 31

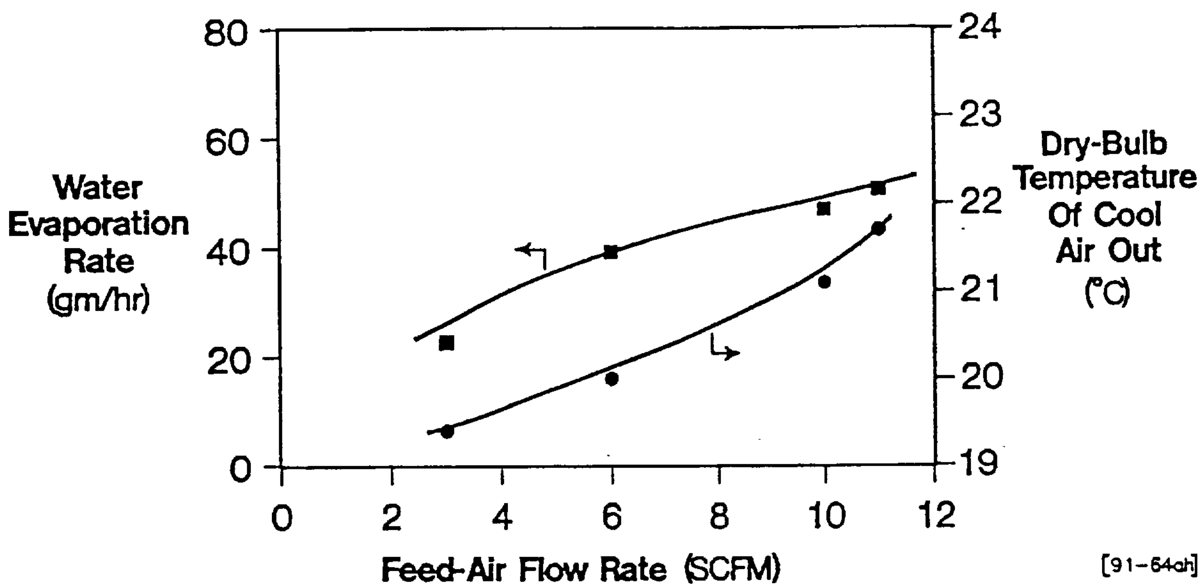


Figure 33. Water-Evaporation Rate and the Dry-Bulb Temperature of Air Stream Exiting Module as Functions of Feed-Air Flow Rate for EVCR

Test Conditions: warm air dry-bulb temperature 27°C
warm air dew-point temperature 13.4°C

III.D. PROCESS-CONTROL LOGIC FOR MEMBRANE-BASED ENVIRONMENTAL-CONTROL SUBSYSTEM

As has been stated above, a goal of this program was to develop a subsystem that required simple and reliable process-control logic. Because the EVCR and WRHE can add or remove water vapor to or from air in a controlled manner, respectively (see Table III and Figure 33), this subsystem can be used to control the humidity and dry-bulb temperature of the CELSS chamber. Figure 34 is a matrix that summarizes the control requirements for this subsystem. As the matrix shows, this subsystem and the control logic to be discussed here can cover all of the reasonable excursions from the basic temperature and humidity set points.

It should be noted that we have not tested the control logic discussed in this section on an experimental apparatus. This

Temperature (Dry-Bulb)		Water-Evaporation Rate: High	Water-Evaporation Rate: Low
	High	WRHE: ON EVCR: OFF	WRHE: ON EVCR: ON
	Low	WRHE: OFF EVCR: OFF	WRHE: OFF EVCR: ON

[91-64d]

Figure 34. Summary of Matrix of Control Requirements

logic is the result only of design studies done using the performance of these membrane components as summarized by Table III and Figure 33. A major goal of the Phase II program will be to test and improve this process-control scheme.

To summarize, the only measurements required are dry-bulb temperatures via a simple and reliable device such as a thermocouple. The control devices here are simply the air blowers forcing air through the hollow-fiber bundles in the WHRE and the EVCR components. The logic of this process-control system is summarized below.

A key characteristic of these PGCs is the large variation in the rate at which of water vapor is transpired into the chamber environment by the plants. When the crop is young or has died (i.e., when there is minimal leaf area), the plants transpire little water into the chamber and effect little cooling. As the crop matures and increases its leaf area, it transpires an increasing amount of water vapor. This high rate of water evaporation provides some cooling effect on the chamber. As was discussed in Section II, a CELSS with conventional components can only react to these changes through energy-intensive reheating.

As will be discussed in detail in Section III.E., to simplify the control of temperature and humidity in the PGC, the membrane-based subsystem is designed such that the total rate at which water vapor is added to the chamber (from plants plus from the EVCR) is constant. This rate corresponds to the maximum rate observed for the plants over their growth cycle. This constant rate of water addition is accomplished by using the EVCR to mimic the transpiration of water vapor by the plants. The feed-air flow rate to the EVCR is controlled such that the rate of water evaporation from the EVCR added to the rate of water transpiration from the plants is equal to the designed water-vapor addition rate. To maintain the humidity in the PGC at the desired level, the WRHE is used to remove water vapor from the chamber at a rate equal to the addition rate. To summarize, the humidity in the PGC is controlled by adjusting the blower to the EVCR.

The way the membrane-based subsystem controls temperature in the PGC is somewhat more complicated. First, the growth lights in the PGC add energy the chamber. A large portion of this energy is converted into sensible heat, which must be removed to prevent the temperature in the PGC from increasing.

In our proposed control scheme, this sensible heat is removed from the PGC in two ways. First, as water is transpired (by plants) or evaporated (by the EVCR) in the PGC, sensible heat in the PGC is converted into latent heat. By adjusting the feed-air flow rate to the EVCR, the amount of sensible heat converted to latent heat can be controlled. The latent heat is subsequently removed from the PGC by the WRHE as it removes water vapor.

The second way sensible heat is removed from the PGC is through cooling of the air circulated through the WRHE. Because sensible heat in the PGC is converted to latent heat at a constant rate (recall that the rate at which water is evaporated in the chamber is constant), the amount of sensible heat that must be removed by the WRHE is also constant (assuming the energy input to the chamber is also constant). To summarize, provided the WRHE is removing sensible heat at the designed rate, the temperature in the PGC is controlled by adjusting the feed-air flow rate to the EVCR, thereby controlling the rate at which sensible heat is converted to latent heat.

As stated above, the feed-air flow rate to the EVCR is controlled from dry-bulb temperature measurements. Because the amount of sensible heat converted to latent heat in the PGC is less than the total energy input into the chamber, there will be a temperature rise in the air as it passes through the chamber. Under steady-state conditions, this temperature rise will be constant.* This means that the dry-bulb temperature at the exit from the chamber (Thermocouple B in Figure 35) will be higher than the dry-bulb temperature in the first section of the chamber (Thermocouple A in Figure 35).

This temperature rise across the PGC is used in our process-control logic to maintain constant conditions in the chamber. For example, if the rate at which sensible heat is converted to latent heat is too low, the rate at which water is evaporated is too low, thus increasing the temperature rise across the chamber.

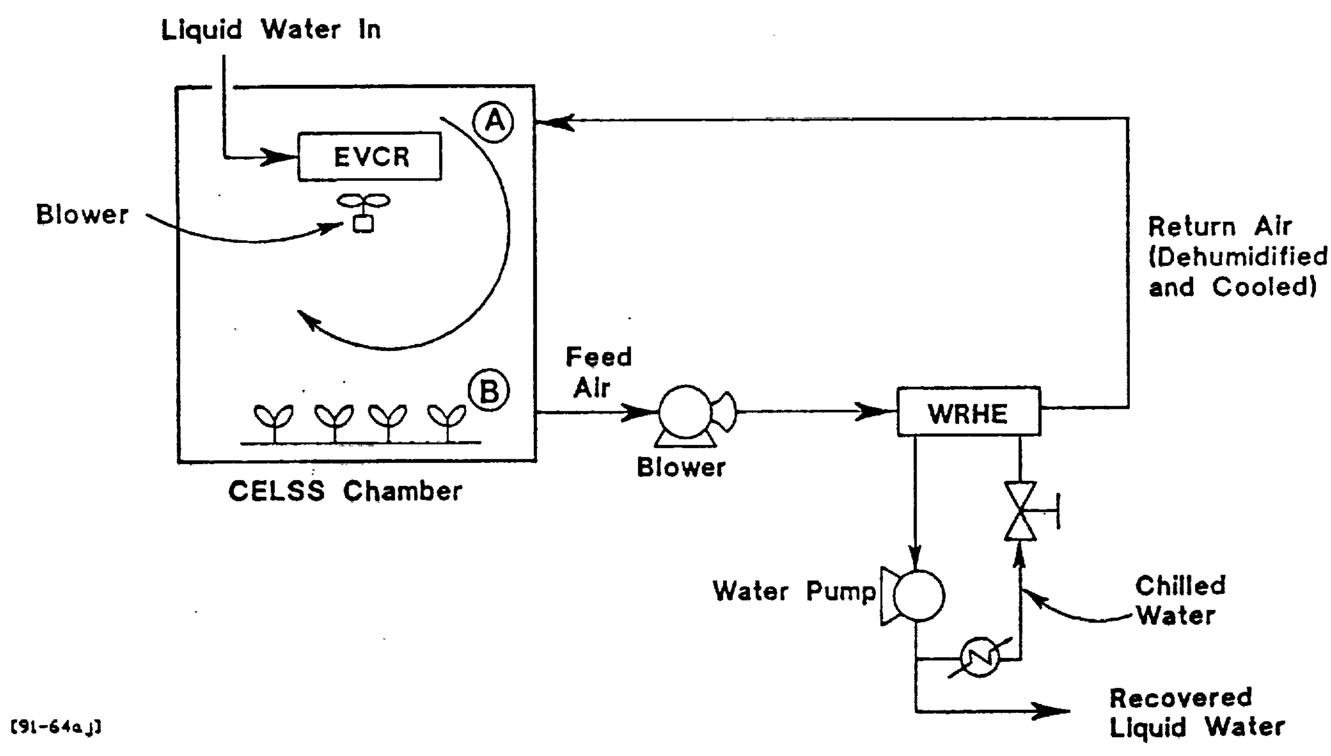


Figure 35. BRI Membrane-Based Subsystem Showing Location of Thermocouples A and B

* This allows the PGC to have regions of different temperature--advantageous for growing several different species of plants.

When the process-control system detects a large temperature rise, the feed-air flow rate to the EVCR is increased, increasing the rate at which sensible heat is converted to latent heat. The opposite is true if the temperature rise is less than the design point.

The above process-control scheme assumed that the WRHE was operating at design conditions. In this case, the duty on the WRHE (in terms of removal of both sensible heat and water vapor) is constant. If, however, the WRHE was not operating at the design conditions, the process-control logic could be used to adjust the feed-air flow rate to the WRHE. Increasing the flow would result in more sensible heat and water vapor being removed from the system. The opposite is true for decreasing the flow to the WRHE. Therefore, while the temperature and humidity in the PGC is controlled primary by adjusting the feed-air flow rate through the EVCR, the feed-air flow rate through the WRHE can also be used to adjust temperature and humidity.

The matrix shown in Figure 34 summarizes this scheme. As the matrix indicates, all possible cases are covered in this design. Note, however, that this control logic is only a model at this point. We have not operated the subsystem as a whole yet, and we have not yet validated this control scheme experimentally. These will be primary goals of the proposed Phase II program.

III.E. COMPARISON: MEMBRANE-BASED VERSUS CONVENTIONAL ENVIRONMENTAL-CONTROL SUBSYSTEMS

III.E.1. Conventional and Membrane-Based Subsystem Designs

To perform a meaningful comparison, we believe it is necessary to study two plant-growth situations: 1) minimal plant growth, as would be found in the case of new plants--i.e., little or no water-vapor transpiration, but with full growth lights; and 2) the case of mature plants--i.e., maximum water-vapor transpiration, and with full growth lights. For these two cases we designed the best conventional and membrane-based subsystems. (It should be noted here that the conventional subsystem was designed by BRI personnel. Although we did our best to design an optimum conventional subsystem, we are not experts in this type of system design. The comparison presented here should be studied with this in mind.)

These designs are summarized in Table IV for the conventional subsystem (the components in the table correspond to the design of the subsystem in Figure 5). Table V summarizes the designs for the membrane-based subsystems (the components in the table correspond to the design of the subsystem in Figure 8).

III.E.2. Comparisons

Figure 36 summarizes the comparisons of the two subsystems for the minimum and maximum plant-transpiration cases. Note first the minimum case shown on the left side of the figure. For the conventional and the BRI subsystems, the growth-light energy input to each subsystem is identical. However, the blower-energy input to the subsystem is higher in the

Table IV. Design Details for Conventional Subsystem Components for Maximum and Minimum Plant-Transpiration Cases

	Max. Transpiration	Min. Transpiration
Light power	200 W/m^2	200 W/m^2
Blowers (capacity)	4.5 Nm^3/min	4.5 Nm^3/min
Blowers (power)	100 W/m^2	100 W/m^2
Heater	590 W	0 W
Temperature rise through chamber	1°C	1°C

Table V. Design Details for BRI Membrane-Based Subsystem-Components for Maximum and Minimum Plant-Transpiration Cases

	Max. Transpiration	Min. Transpiration
Light power	200 W/m^2	200 W/m^2
Blower (capacity)	0.055 Nm^3/min	0.055 Nm^3/min
Blower (power)	10 W	10 W
Evaporative cooler	0 W	30 W
Heater	0 W	0 W
Temperature rise through chamber	1°C	1°C

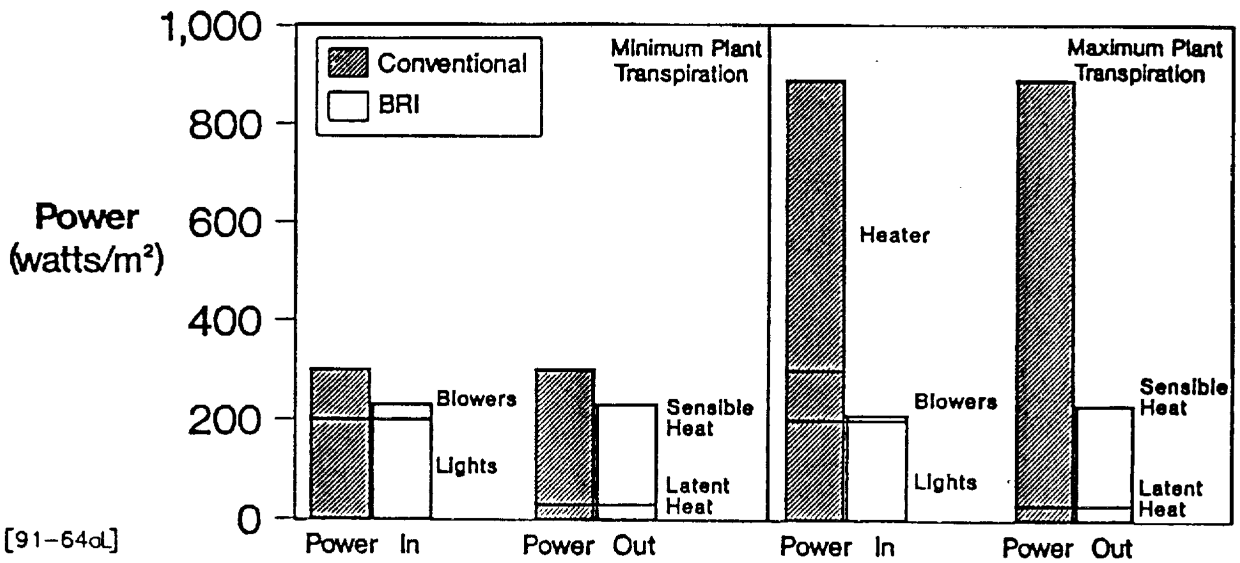


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Figure 36. Comparison of Power Use for Conventional and BRI Membrane-Based Subsystem Design

conventional subsystem. This is because the air-flow rate through the PGC must be relatively high to keep the temperature rise from being too high. (In other words, the air flow must be sufficiently high to remove all the sensible heat from the chamber.) The growth lights are introducing energy to the chamber without the moderation of the dry-bulb temperature due to water-vapor transpiration of the plants.

In the membrane-based subsystem, the EVCRs evaporate water into the chamber at the rate equivalent to the maximum transpiration rate of the plants. This evaporation will moderate the dry-bulb temperature of the chamber as though the plants were transpiring at the maximum rate. This water vapor is eventually removed by the WRHE. Note that the air flow in the membrane-based system is much lower because less sensible heat must be removed in the WRHE since the EVCR cools the air in the chamber.

As Figure 36 shows, at minimum plant transpiration each subsystem removes all of the energy input to the chamber. In the conventional subsystem, there is no water condensed in the condensing heat exchanger. Therefore all of the energy is removed via sensible heat transfer in the condensing heat exchanger. For the membrane-based subsystem, the energy is removed by the WRHE as a combination of sensible heat transfer to the chilled water circulating in the fiber lumens, and latent heat removal due to the condensation of the water vapor on the cold fiber--and ultimate transfer again to the chilled water. Therefore, the fundamental control of temperature is done by the WRHE.

As Figure 36 indicates, in the minimum plant-transpiration case, the membrane-based subsystem is more efficient than the conventional subsystem, but not dramatically so. In this case, the real advantage of the membrane-based subsystem is the barrier to contact between liquid water and air and the lack of a need for a physical phase-separation device.

In the maximum plant-transpiration case, the energy-based advantages of the membrane-based subsystem are more apparent. Here, energy inputs to the PGC from lights are still the same for each subsystem. Further, the same blower power is still required as for the minimum transpiration case for BRI and conventional subsystems.* The significant difference in energy inputs comes from the necessity to reheat air in the conventional design. The high air flow results in the system removing the same amount of sensible heat as removed in the minimum transpiration case. Thus, because the air must be cooled to the dew-point temperature corresponding to the amount of water removed, the return air must be reheated to maintain the appropriate dry-bulb temperature in the chamber.

The membrane-based subsystem, in fact, has a lower total energy input in the maximum plant-transpiration case than in the minimum plant-transpiration case. This is because little air (or no air, in the true maximum case) is blown through the EVCR. No evaporation by the EVCR is necessary as the plants are adding the design load of water vapor by definition.

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* We have assumed here that to simplify the design and operation of the conventional system, the same air blower would be used for the maximum transpiration case as the minimum. This eliminates the need for a variable-speed blower and a complicated control scheme.

For the conventional subsystem, energy removal for the maximum plant-transpiration case is dominated by the removal of sensible heat from the condensing heat exchanger as it cools the air stream to the required dew-point temperature (as discussed above). The energy removed as latent heat for the conventional subsystem corresponds to the condensation of the transpired water in the condensing heat exchanger.

In the BRI membrane-based subsystem, energy removal is essentially the same total amount and relative amounts of sensible and latent heat as for the minimum plant-transpiration case. This is because the amount of water transpired by the plants in this case is the same as the amount transpired by the EVCR in the minimum case. This is the key to the operation and ease of control of the BRI membrane-based subsystem--the load on the WRHE is constant for any set of conditions. The only difference, again, is the blower power for the EVCR required in each case. As a final comparison, Figure 37 shows the cycles of the two processes on a psychrometric chart for the maximum plant-transpiration case.

The membrane-based subsystem also offers two other key advantages over the conventional subsystem. First, the condensing heat exchanger requires technology for the recovery of water droplets from the air stream exiting it. The existing technology for this application is complicated and inefficient (Blackwell et al., 1991). The membrane-based subsystem--specifically the WRHE--does not require any such technology. It produces a liquid-water stream with little or no dissolved or entrained air. (In fact, the WRHE could serve as the air/water-droplet phase separator should condensing heat exchangers be used.)

The second key advantage is that neither of the two membrane processes (i.e., the EVCR or the WRHE) require contact between liquid water and the air stream. This is of great interest in avoiding microbial growth and is a major disadvantage of a condensing heat exchanger.

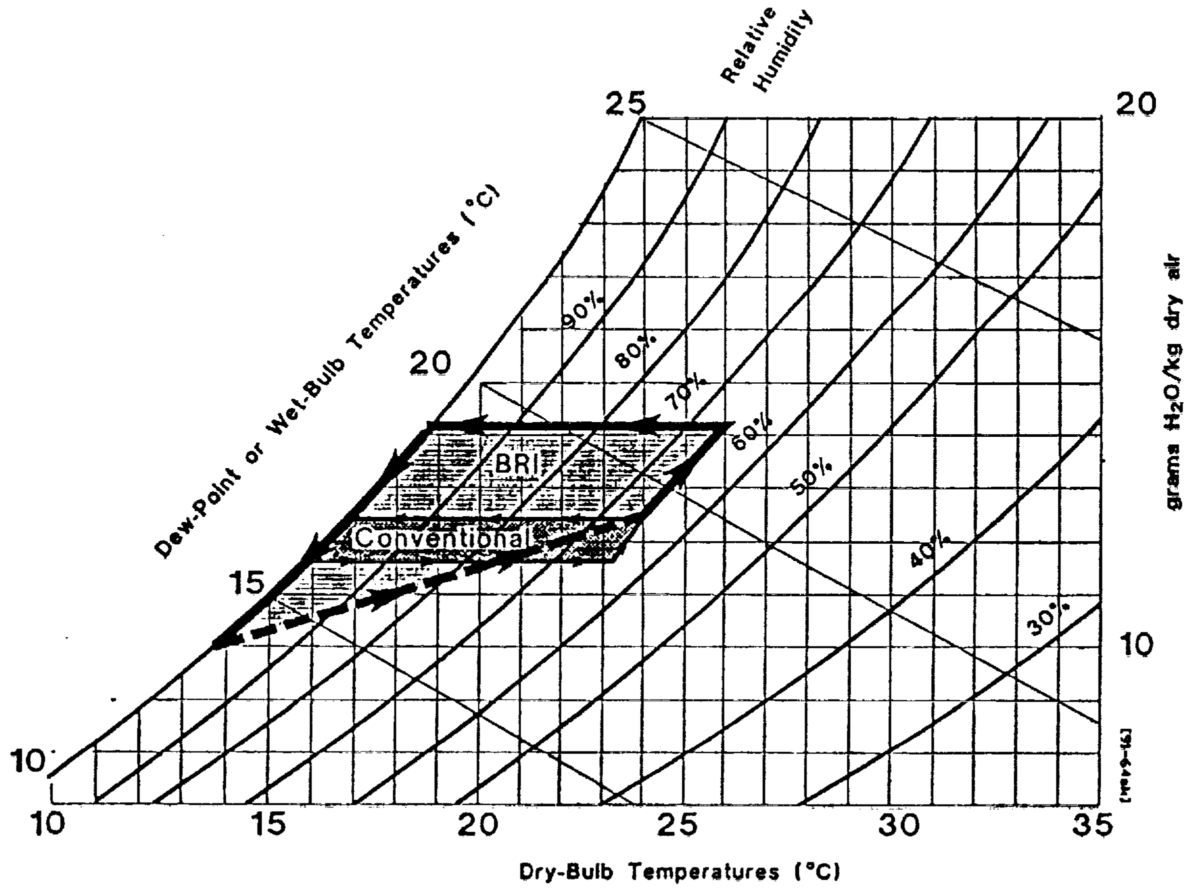

Figure 37. Representation of Change of Air-Stream State for Conventional and BRI Processes for Maximum-Transpiration Case

IV. CONCLUSIONS AND RECOMMENDATIONS

The Phase I program was successful. We reacted to NASA input and feedback in the early stages of the program and improved the technology significantly over that proposed in the Phase I proposal. The results of this Phase I program have established that this membrane-based subsystem is a promising method of controlling the environment of a CELSS chamber. Furthermore, the WRHE technology--conceived of and preliminarily developed here--may have general applicability to other NASA applications for which water vapor or water droplets must be separated from a gas stream.

Further conclusions are as follows:

1. The inherent packing density of these hollow-fiber membrane modules promises to result in low-mass and low-volume technologies for use in space applications.
2. The use of chilled water (perhaps readily available in the spacecraft or base) and low-power air blowers offers the potential for this to be an energy-efficient technology.
3. The heat- and water-removal subsystem based on this technology should be highly reliable. There are very few moving parts in these technologies, and they are all external to the membrane modules themselves.
4. The hollow-fiber technologies to be used here have few components. This will simplify qualification of this technology for flight.
5. The process-control measurement variables (dry-bulb temperature via thermocouples) and the control logic are very simple and should be reliable.
6. The Water Recovery Heat Exchanger (WRHE) promises to be a generic technology useful for a variety of NASA applications. Preliminary results from this program indicate that this technology can separate water vapor

and/or water droplets from gas streams. It should work well in microgravity environments.

7. The Evaporative Cooler (EVCR) is key to the subsystem under development here. It also may well have utility in providing an air stream (or other gas stream) with a given humidity in a microgravity environment. This may be of use in certain experiments by NASA.

We recommend that NASA proceed with Phase II of this program. The proposed Phase II deliverables are a breadboard subsystem and a final report containing baseline data to aid in the design of a subsystem suitable for flight testing--perhaps as part of the CELSS testing program. The breadboard subsystem will allow NASA personnel to validate the data produced in Phase II and to generate new data for use in supporting this flight-test program.

Other specific recommendations follow:

1. An extensive module-development program is necessary, with the goal of obtaining modules best suited for the EVCR and for the WRHE applications. These modules should be designed to have the highest possible overall transport coefficient with the minimum power and weight tradeoff.
2. The process-control scheme conceived of during this program should be validated and the design improved as much as possible.
3. The integrated subsystem design conceived of during the Phase I program should be tested and improved.
4. Long-term tests of the subsystem and of each component should be performed.
5. The subsystem and each component should be tested under extreme conditions to identify as many failure modes as possible.

6. The ability of the WRHE to purify the water vapor recovered from the CELSS chamber should be determined and, if possible, improved upon.

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APPENDIX A

In the Phase I proposal and initially in the Phase I work, we focused on development of a temperature-control and water-recovery subsystem based on two membrane technologies previously developed at BRI for NASA and other clients. This subsystem employs 1) membrane-based dehumidification modules to remove water vapor from air, and 2) "membrane contactor" technology to return water vapor to the CELSS chamber (and in so doing control the temperature and humidity levels within the PGC). The first of these modules, the dehumidification module (DEHM), removes water vapor from an air stream in the gas phase without the need to condense the water in the air stream as does a conventional dehumidification system.

This process potentially uses less energy to dehumidify since there is no need to cool the air stream below its dew-point temperature with subsequent reheating to the desired return-air temperature. This type of membrane module employs a vacuum pump to provide the driving force for water vapor to permeate the membrane.

The DEHM, teamed with a EVCR, can efficiently control the temperature and humidity levels in a PGC environment. A schematic of this system design appears in Figure A-1, and the thermodynamic pathway for the system is plotted on a psychrometric chart in Figure A-2.

To validate this design, dehumidification modules were studied with the test apparatus found in Figure A-3 under the conditions likely to be found in a PGC (Kliss, 1991). The baseline conditions for the testing the modules are found in Table A-I.

Test conditions were varied from the baseline conditions to determine performance of the dehumidification modules as a function of the following parameters:

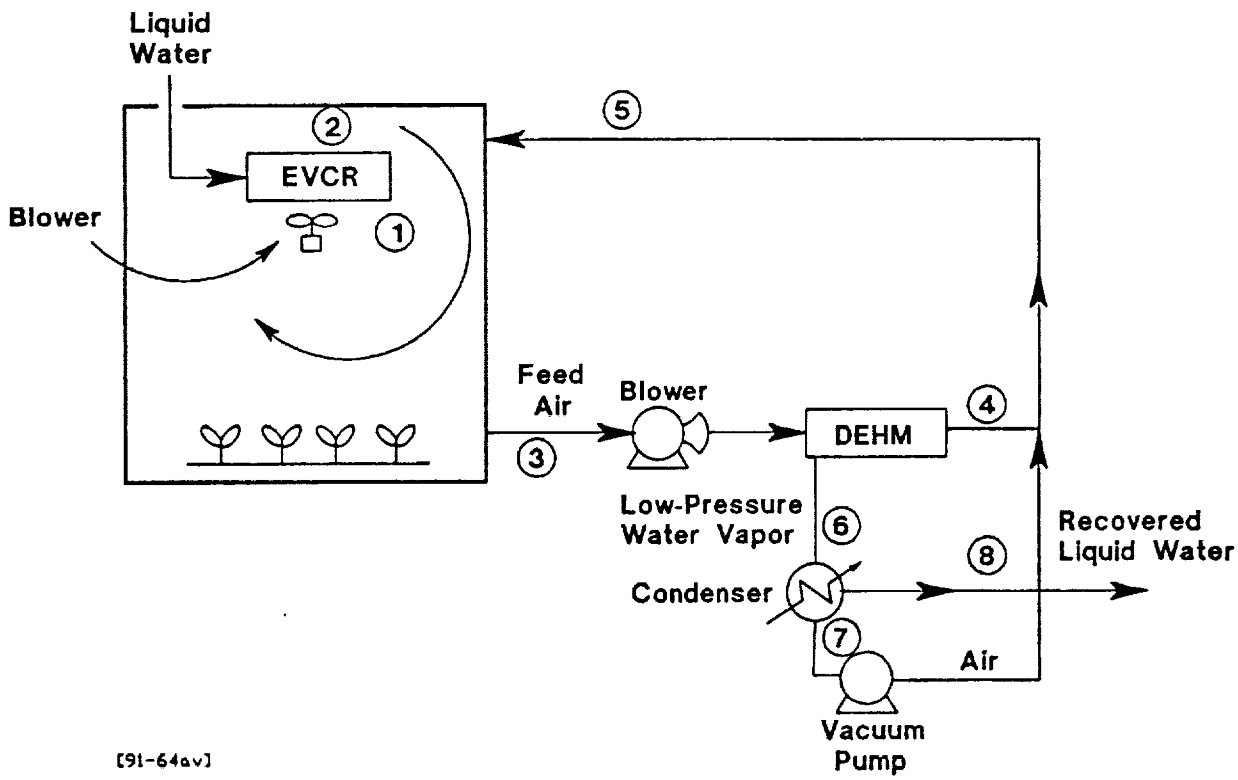

Figure A-1. Schematic of CELSS Subsystem Design with DEHM and EVCR Technology

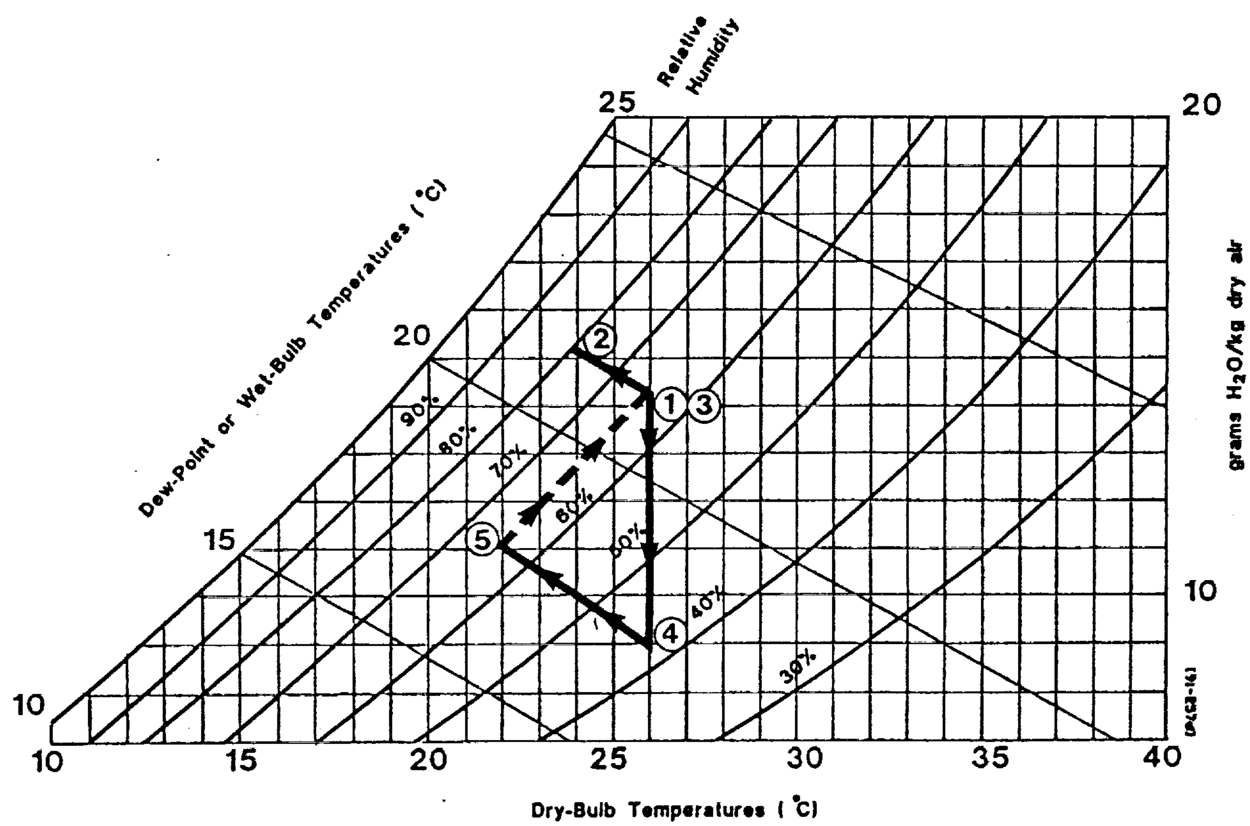

Figure A-2. Representation of Air Stream Change of State through CELSS with DEHM and EVCR Technology

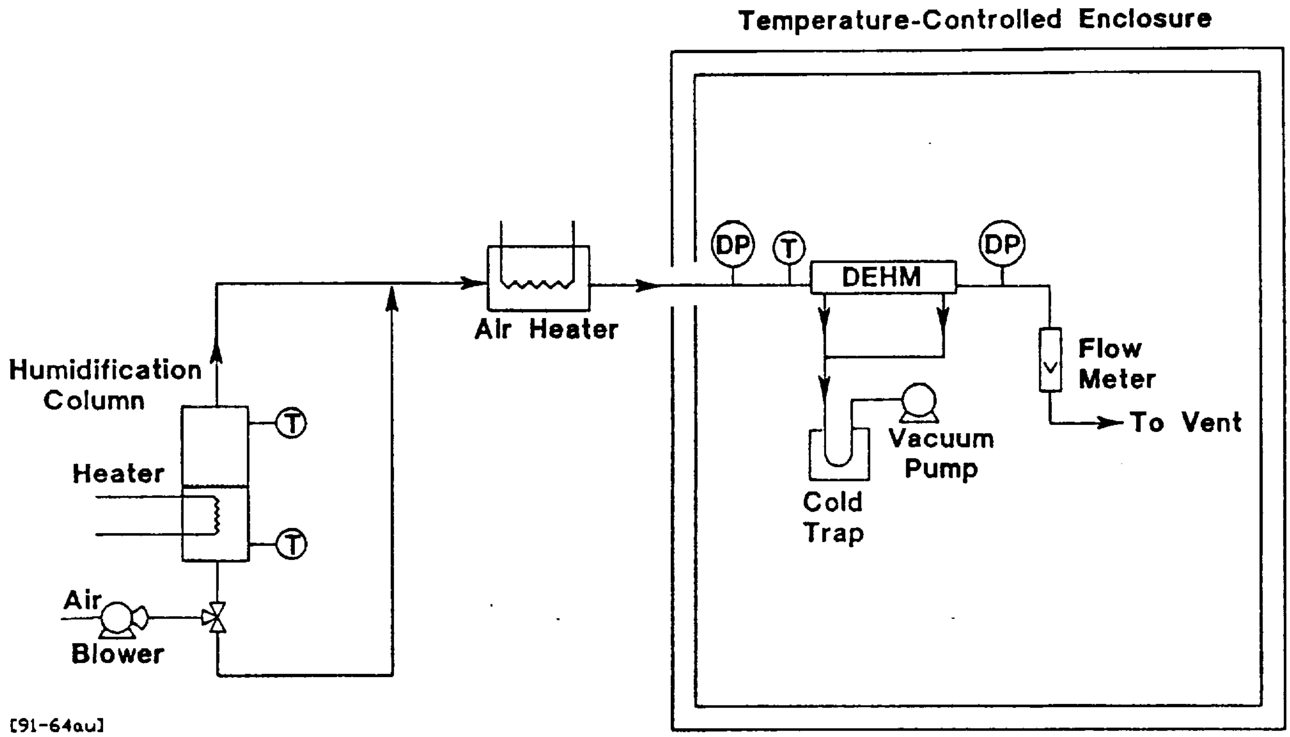

Figure A-3. Experimental Apparatus for DEHM Module

Table A-I. Baseline Conditions for DEHM Tests

Item	Value
Dry-bulb temperature	26°C
Dew-point temperature	22°C
Feed flow	0.16 m^3/min
Permeate pressure	10 mmHg

1) feed flow,
2) feed dew-point temperature,
3) feed dry-bulb temperature,
4) feed relative humidity, and
5) permeate pressure.

The raffinate dew-point temperature is plotted as a function of feed-flow rate in Figure A-4a, and the water-recovery rate as a function of feed-flow rate in Figure A-4b. As is expected,

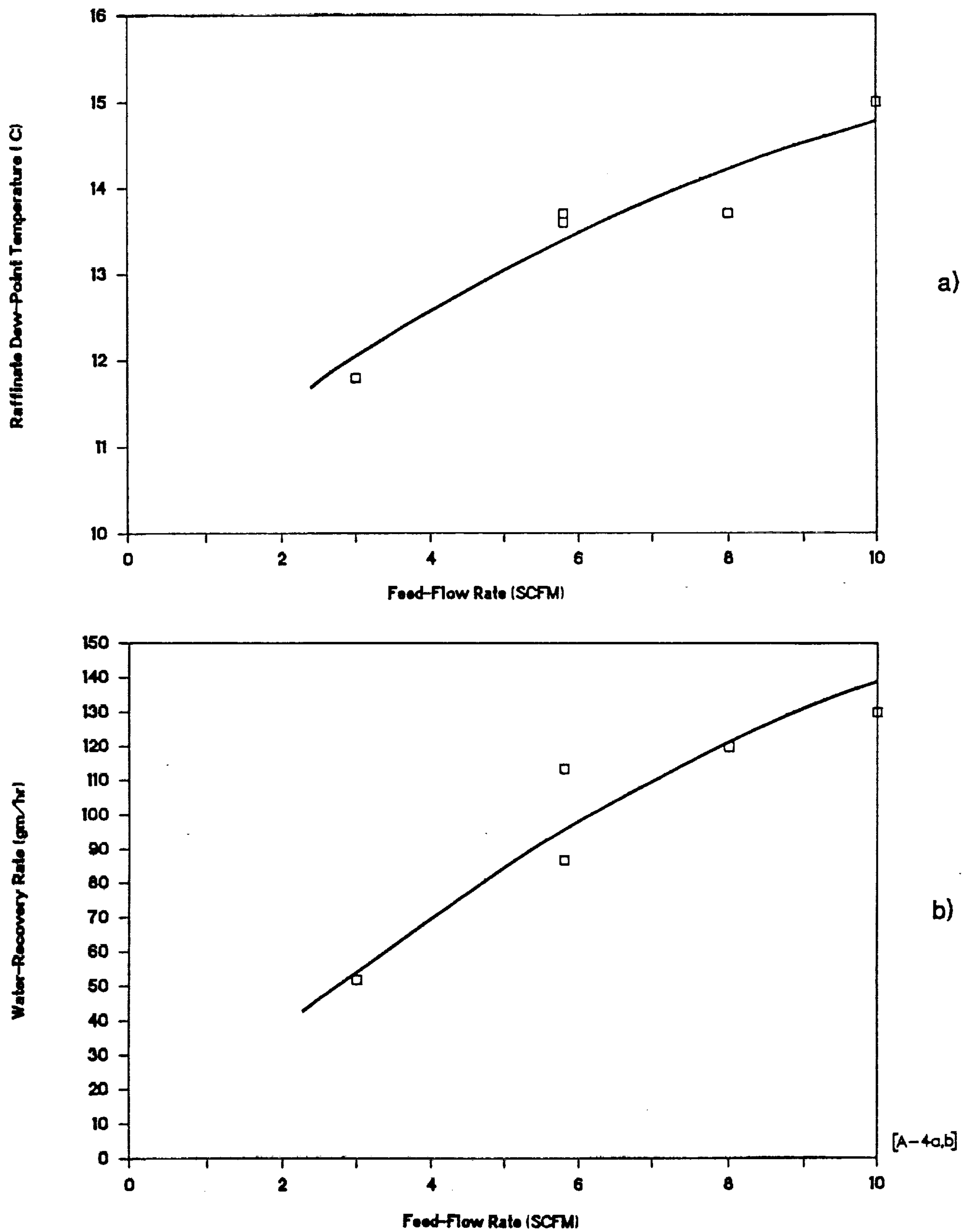

Figure A-4. Raffinate Dew-Point Temperature (a) and Water-Recovery Rate (b) as Functions of Feed-Flow Rate through DEHM Module higher flow rates yield a higher water-recovery rate since the average concentration of water vapor is higher with higher flows. The raffinate dew-point temperature rises with higher flows (indicating a more humid product stream) despite the greater amounts of water being removed. This is because the fraction of water vapor recovered from the feed is less at higher flows, even though the absolute amount of water vapor recovered is greater.

The raffinate dew point is plotted as a function of feed dew-point temperature in Figure A-5a, and the water-recovery rate as a function of feed dew-point temperature in Figure A-5b. As expected, the water-recovery rate increases with increasing water-vapor concentration in the feed.

The raffinate dew point is plotted as a function of feed dry-bulb temperature in Figure A-6a, and the water-recovery rate as a function of feed dry-bulb temperature in Figure A-6b for constant feed dew-point temperature. The water-recovery rate, and hence the mass-transfer coefficient, drops with increasing dry-bulb temperature. Normally, mass transfer is enhanced with temperature increase. In this case, water-vapor activity (which decreases with temperature) has a dominant influence on transport, overwhelming other gains due to higher temperature.

The raffinate dew point is plotted as a function of constant relative humidity (RH) at varying temperature in Figure A-7a and the water-recovery rate in Figure A-7b. Note in Figure A-7b that the relation of water recovery to feed temperature at constant RH is linear. This suggests that the mass transport in this system is a linear function of RH. Stated another way, this suggests that the RH, and hence the water-vapor activity, influences mass transfer. The relation of RH to mass transfer is discussed below.

The investigations mentioned thus far have been concerned with manipulating parameters on the feed side of the membrane. Permeate-side parameters also influence mass transfer. The partial-pressure difference between the feed and permeate is the

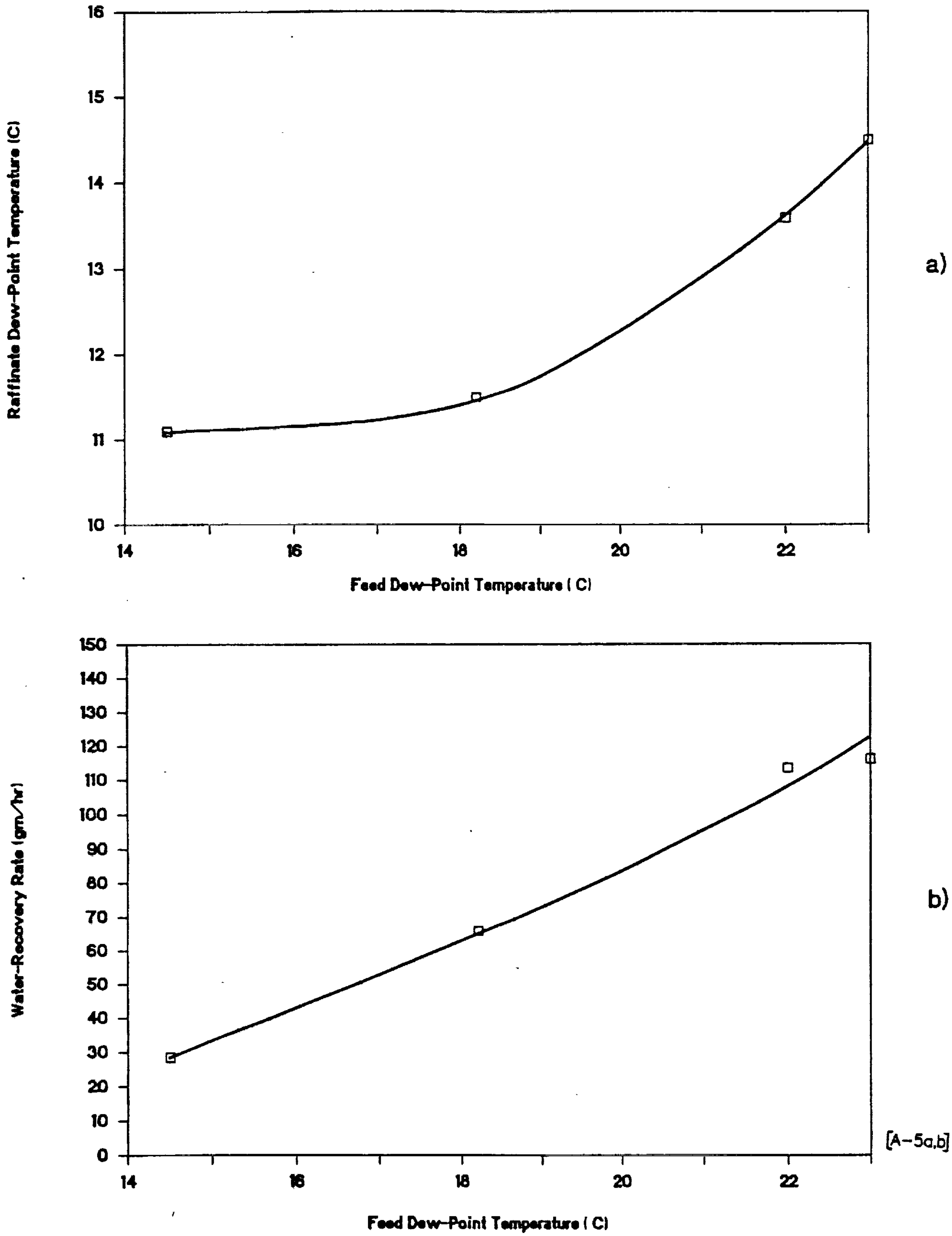

Figure A-5. Raffinate Dew-Point Temperature (a) and Water-Recovery Rate (b) as Functions of Feed Dew-Point Temperature for a DEHM Module

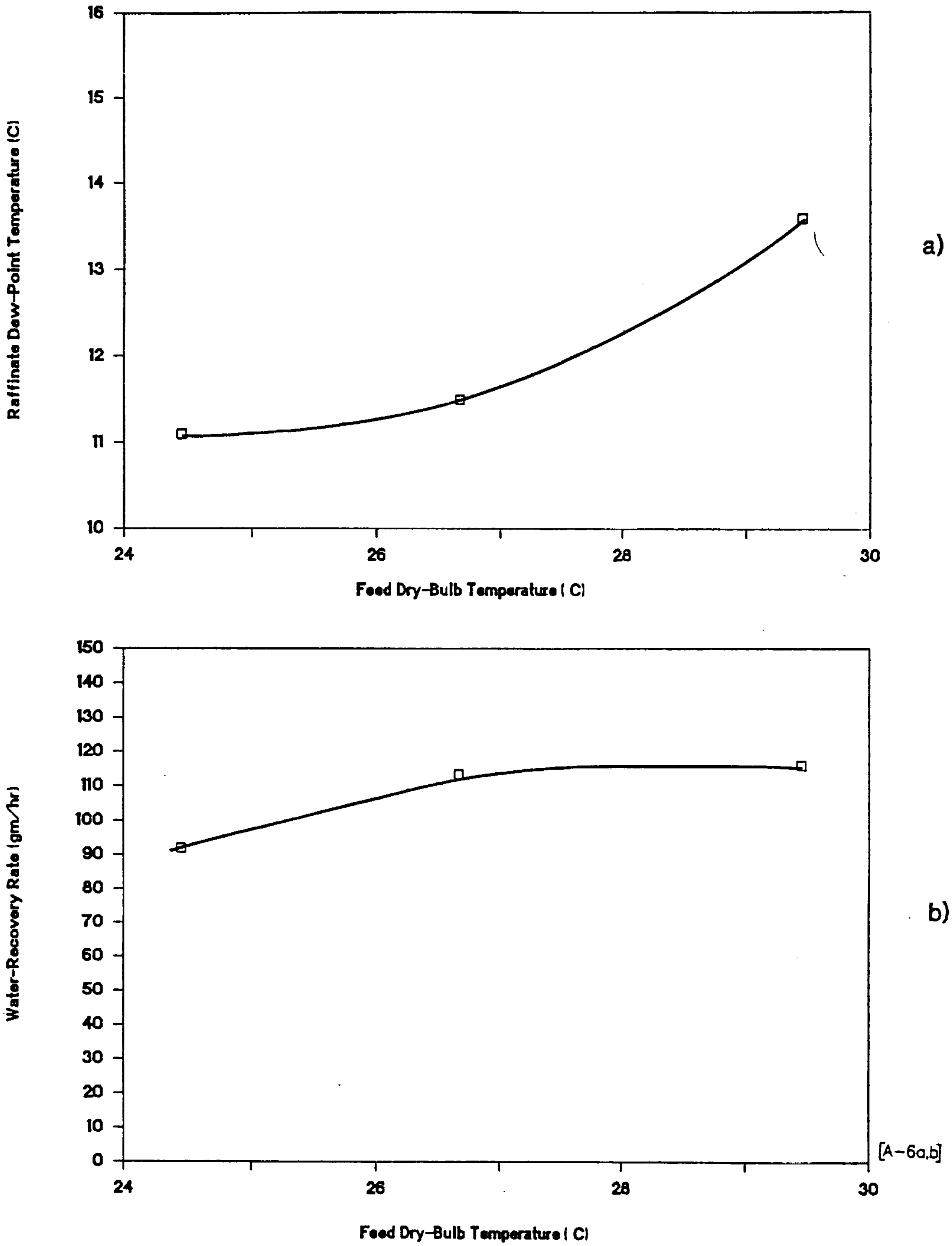

Figure A-6. Raffinate Dew-Point Temperature (a) and Water-Recovery Rate (b) as Functions of Feed Dry-Bulb Temperature for DEHM Module Operating at Constant Feed Dew Point of 13°C

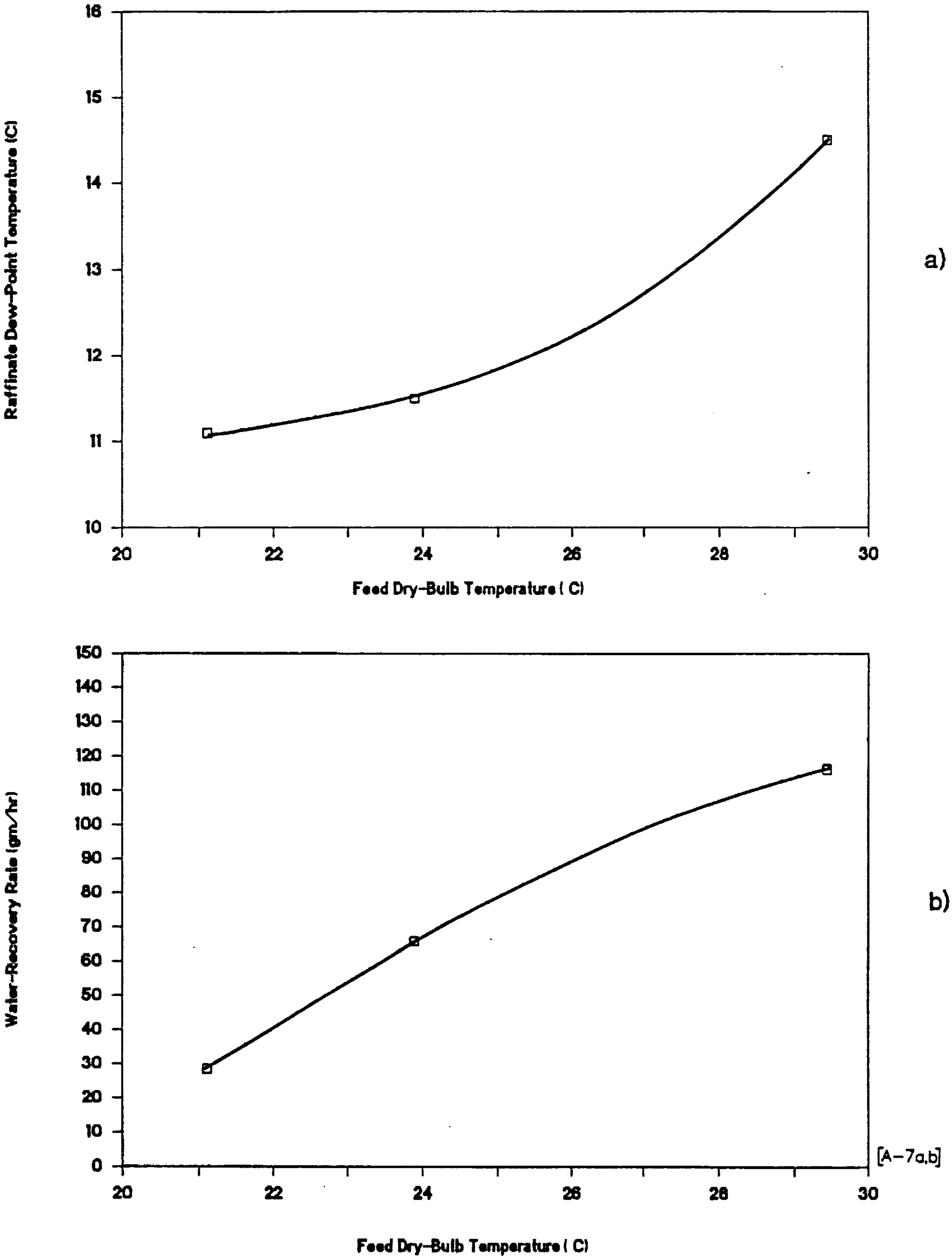

Figure A-7. Raffinate Dew-Point Temperature (a) and Water-Recovery Rate (b) as Functions of Feed Dry-Bulb Temperature for a DEHM Module Operating at Constant RH of 70%

main driving force. Altering the permeate pressure changes the driving force and mass transfer. The raffinate dew point is plotted as a function of permeate pressure in Figure A-8a, and the water-recovery rate as a function of permeate pressure in Figure A-8b. As expected, the water-recovery rate is inversely proportional to permeate pressure.

The measurements of quantity of water recovered and raffinate dew-point temperature were used to determine an overall mass-transfer coefficient. A statistical investigation of the experimental results sought to correlate mass-transfer coefficients to feed and raffinate dry-bulb temperatures, dew-point temperatures, flow rates, and RH. The investigation showed a correlation of mass transfer proportional to the square root of feed flow and proportional to feed RH. These correlations allow the addition of feed-RH and feed-flow corrections to the mass-transfer model, resulting in greater accuracy. Since the DEHM technology is not being pursued, a detailed description of the mass-transfer model is beyond the scope of this report.

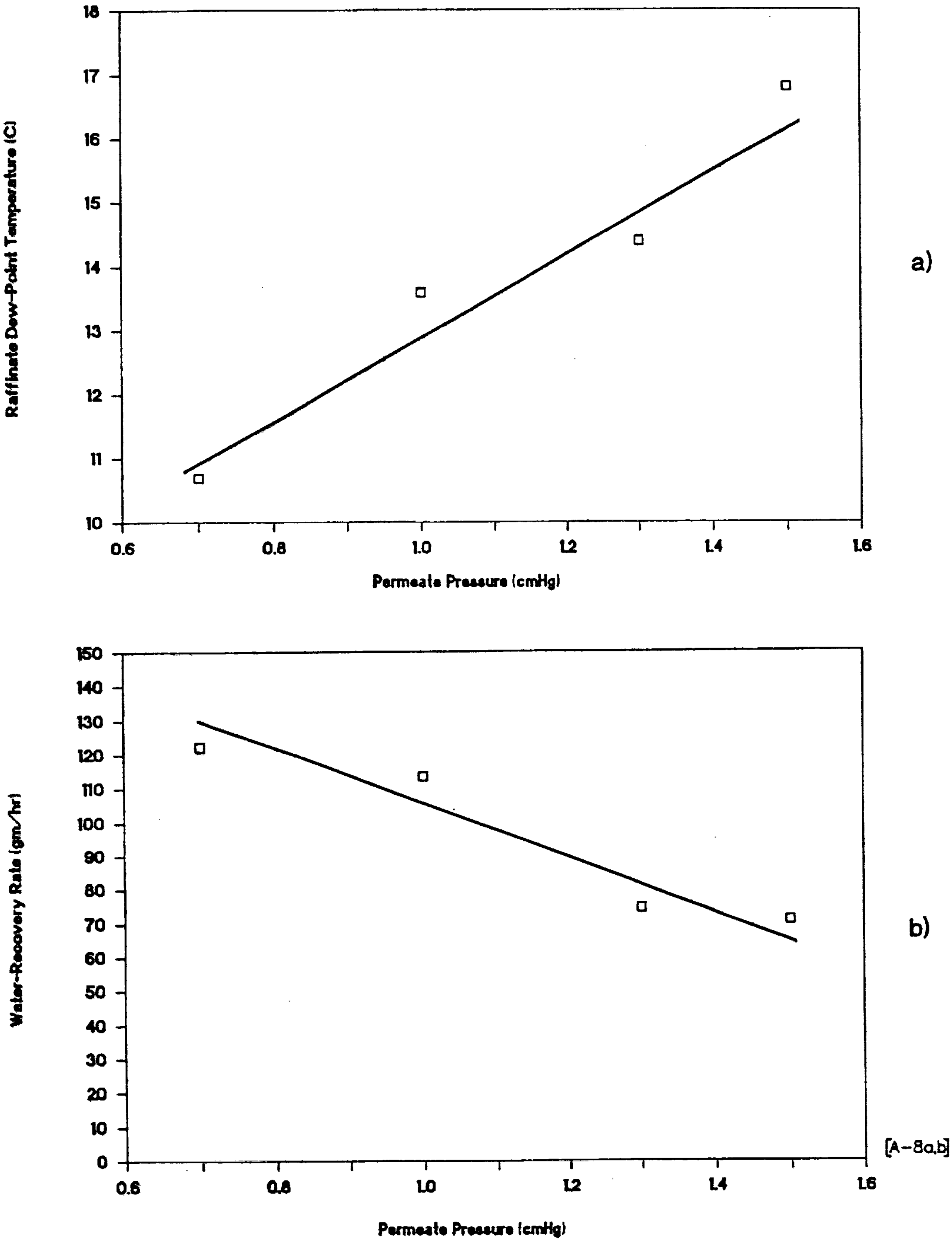

Figure A-8. Raffinate Dew-Point Temperature (a) and Water-Recovery Rate (b) as Functions of Permeate Pressure for a DEHM Module

PROPRIETARY ADDENDUM

The information in the Proprietary Addendum Section of this proposal constitute a trade secret and/or information that is commercial or financial and confidential or privileged. It is furnished to the Government in confidence with the understanding that it will not, without permission of the offerer, be used or disclosed other than for evaluation purposes; provided, however, in the event a Phase II contract is awarded the Government may obtain additional rights to use and disclose this information.

Item #1

As shown in Figure 8, the liquid-water stream is kept at a reduced pressure in the WRHE, as is explained later. The pressure at the outlet of the circulation pump is kept slightly above ambient to allow the net water recovered from the air stream to be bled from the system and sent to a posttreatment subsystem for processing and reuse, where appropriate.

Item #2

The heart of this system is a membrane contactor containing nonporous, hydrophilic hollow-fiber membranes. The nonporous nature of these fibers prevents air from entering the liquid-water stream in the fiber lumens.

Item #3

First, the fibers are made of regenerated cellulose, which is an extremely hydrophilic polymer--i.e., the water will partition very favorably out of the air and into the polymer. Put another way, condensed water will very favorably wet the polymer. In fact, this polymer is so hydrophilic that the fiber wall can be modeled as a water layer. Therefore, the high selectivity of water vapor over air comes from the extremely low solubility of air in water. Air will only cross the membrane by diffusion, and this will be an extremely low transport rate.

Item #4

The key to making this device work without fog or water-droplet formation on the shell side of the module is for the transport of water from the vapor state in the feed-air stream to the liquid-water stream in the fiber lumen to be limited by the rate of condensation of the water vapor at the fiber surface. In this way, the water will not accumulate on the fiber surface and condensation and fog formation is avoided.

The transport of water vapor across the membrane is effected by lowering the pressure of the bulk liquid water in the fiber lumen. This is the third factor necessary for the operation of this device. This was achieved in our experiments by the method shown in Figure 16. The liquid water is "pulled" through the fiber lumens by a pump, with the water passing through a throttle valve immediately upstream of the module. This results in pressures as low as 0.1 atm in the liquid phase. This low pressure provides the driving force for transport of water vapor across the hollow-fiber wall. Water is pulled from the fiber wall into the bulk flow and swept out of the fiber lumen and into the pump. The transport of water vapor across this type of hollow-fiber membrane is described by the equation

$$J_L = \Delta P \cdot k_m \cdot A, \qquad (2)$$

where

J_L = flux of liquid water (gm/hr),

ΔP = transmembrane pressure (atm),

k_m = mass-transfer coefficient (gm H_2O/hr-m^2-atm), and

A = area (m^2).

The permeability (the maximum mass-transfer coefficient) of such a fiber is typically 3500 gm H_2O/hr-m^2-atm.

To ensure that fog or water drops do not form on the shell side of the module, the water flux through the membrane (Equation 2) must be greater than the rate of condensation (Equation 1). This means that the transmembrane pressure must be sufficiently large to "pull" all the condensed water through the fibers. Under the conditions the WRHE will operate under in this application, we estimate that the minimum transmembrane pressure to accomplish this at 0.01 atm. Thus, the lumen water pressure must be kept below 0.99 atm to ensure that transport of water is limited by condensation and not by membrane transport.

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Item #5

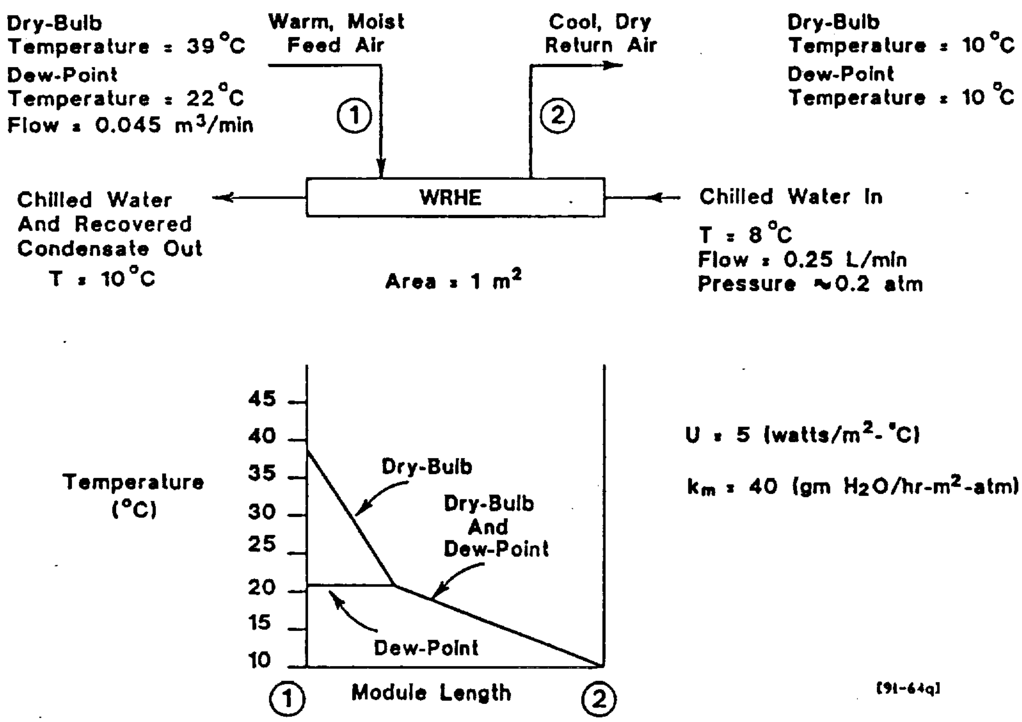

Figure 17. Summary of Experimental Run of WRHE

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Item #6

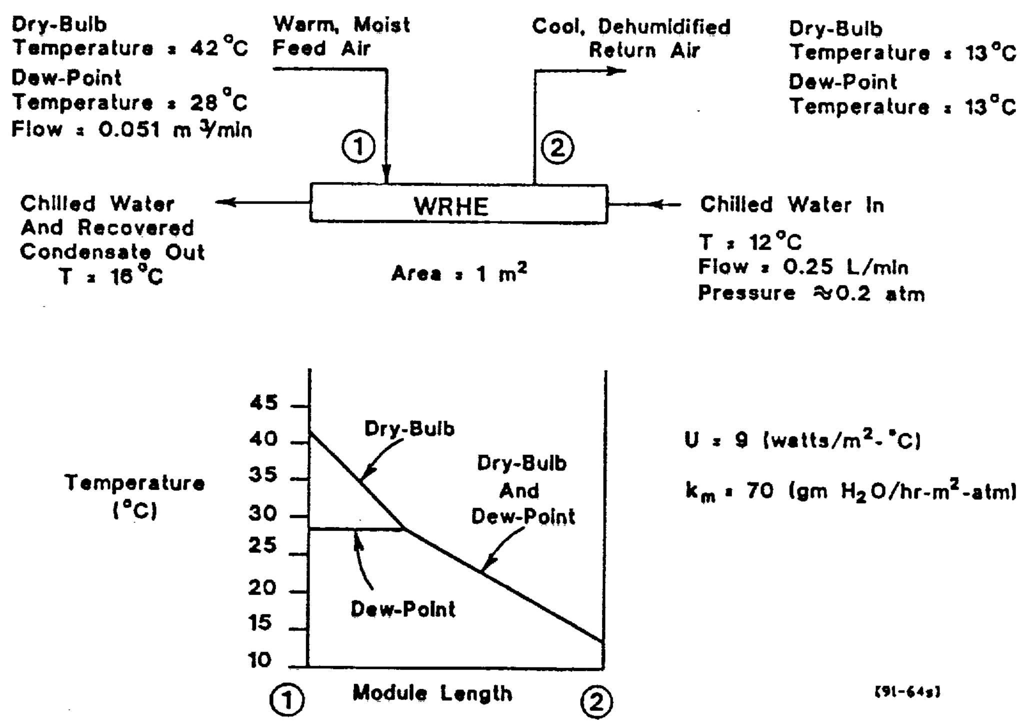

Figure 19. Summary of Experimental Run of WRHE

Item #7

These fibers are made at Bend Research from polyethersulfone, a relatively hydrophobic material, and as such are not well-suited for the mass-transfer aspect of this application. This is because this type of fiber does not imbibe water, due to its hydrophobic nature. This results in the fiber being unable to transport water vapor at a rate high enough to balance the rate of condensation at the surface. Thus, fog or water droplet will form.

PROPRIETARY ADDENDUM

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<u>Item #8</u>

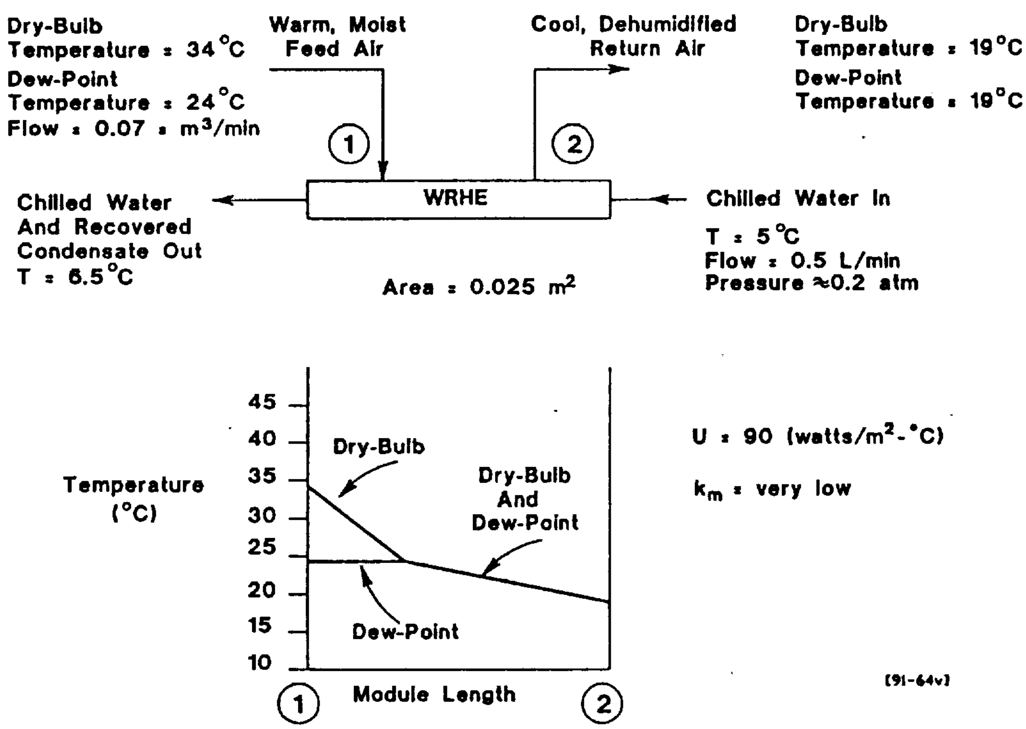

Figure 22. Summary of Experimental Run of WRHE

<u>Item #9</u>

Because this last experiment was performed with the hydrophobic fibers, we were unable to determine a meaningful mass-transfer coefficient. Interestingly, in fact, we did observe fog and water-droplet formation inside the shell of these modules. This was to be expected, as the mass transfer through these fibers is low. In this case, then, the rate of condensation is higher than the rate of transport of water through the fiber wall. It is clearly important to use the proper type of fiber material.

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Bioregenerative systems—life-support systems to regenerate oxygen, food, and water—are key to establishing man's permanent presence in space. NASA is investigating the use of plant-growth chambers (PGCs) for space missions and for bases on the moon and Mars. PGCs serve several important purposes, including 1) oxygen and food production, 2) carbon-dioxide removal, and 3) water purification and reuse. Key to successful development of PGCs is a system to recover and reuse the water vapor that is transpired from the leaves of the growing plants.

In this program we propose to develop a simple, reliable membrane-based system that allows the recovery, purification, and reuse of the transpired water vapor through control of temperature and humidity levels in the PGC. This sytem has characteristics that make it ideally suited to use in space—1) minimal power requirements, 2) small volume and mass, 3) simplicity, 4) reliability, and 5) versatility.

In Phase I we will 1) develop an accurate, predictive model of our temperature- and humidity-control system, based on parametric tests of membrane modules; and 2) use this model to design systems for selected PGCs. In Phase II, we would seek to design, fabricate, test, and deliver a breadboard unit to NASA for testing on a PGC.

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